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THE INFLUENCE OF HOUSING SYSTEMS ON MOISTURE AND GASEOUS CONTAMINANTS REMOVED BY VENTILATION

by

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The undersigned certify that they have have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled "The Influence of Beef Housing Systems on Moisture and Gaseous Contaminants Removed by Ventilation" submitted by John Jerry Raymond Feddes in partial fulfilment of the requirements for the degree of Master of Science.

ABSTRACT

The principle object of this project was to investigate the influence of fully slatted and straw-bedded beef housing systems on moisture and gaseous contaminants removed by ventilation. Each housing system included two exhaust levels for removal of the gaseous contaminants produced by the cattle and their wastes. Sampling procedures involved monitoring ammonia and carbon dioxide concentrations and the water vapour removed at each exhaust level from each of the two housing systems. Ammonia and carbon dioxide also were monitored at animal level. A moisture balance was established for each housing system and exhaust level,with the moisture entering the housing facilities via the inlet air, as consumed water and as the moisture in the feed to the cattle being measured along with the accumulated moisture in the manure pack and in the liquid waste pits.

The analyses included the effects of operating aeration agitators in the liquid wastes stored beneath the slatted floor and the effects of two ventilation rates used in the straw-bedded housing system on the removal of these gaseous contaminants. For the purpose of statistical analysis, the water vapour, ammonia, and carbon dioxide removal rates were expressed in terms of liveweight and ventilation.

Statistical analysis of the data revealed that exhaust levels significantly affected the water vapour and ammonia removal rates while the rate of carbon dioxide removal was not significantly affected. When three agitators were aerating the liquid wastes in the slatted-floor housing system, no practical differences in vapour removal rates were found between the two housing systems. No practical differences

also were found in the concentrations of ammonia and carbon dioxide removed from the two housing systems which included the different degrees of agitation in the slatted-floor housing system. In the straw-bedded housing system, the lower ventilation rate removed more vaporized moisture than the higher ventilation rate when expressed in terms of liveweight and air exchange rate. With no agitation of the liquid wastes occurring in the slatted-floor housing system, the ratio of the water vapour removal rates for the slatted and straw-bedded systems was 0.82.

The moisture balance analyses indicated that 43-73 per cent of the moisture input was removed by ventilation, depending on the housing system, degree of aerobic treatment and exhaust level. Multiple regression analysis indicated that complex interactions existed between the independent variables used to explain the variation in the levels of water vapour, ammonia, and carbon dioxide removed by ventilation. In the slatted-floor housing system, ammonia concentrations were found to be greater at animal level than in the exhaust air when the upper exhaust level was in operation. The reverse situation occurred when the lower exhaust system was in operation.

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1. INTRODUCTION

Developments in total confinement housing systems in recent years have played a critical role in many areas of livestock production by ensuring a level of operational efficiency not considered possible less than a generation ago. The increasing size of confinement production units, however, is causing concern, not only with regard to their much publicized effects on environmental quality, but also with respect to the air quality within the units themselves.

The introduction of slatted floors, which allow the storage of manure in pits under these floors for long periods of time, has added to this concern since these wastes produce various noxious gases and strong odours as a result of bacterial decomposition. Air contaminants within the animals immediate environment may include water vapour, gases, dust, and pathogenic microorganisms . Moisture and gas production are the primary causes of contaminants within confinement production units of livestock. Water vapour production within confinement housing is a result of respiration from the animals, evaporation from waterers, and animal wastes in the liquid and solid forms. Its effects are usually measured in terms of relative or absolute humidity of the air.

Gases found in livestock buildings are usually the by-products of respiration, fermentation and biological degradation of organic compounds. Carbon dioxide and, in the case of ruminants, methane are the primary constituents of the air exhaled by livestock. Along with these gases, ammonia, hydrogen sulphide and sulphur dioxide may also be released by biological decomposition of stored animal wastes. The agitation of liquid slurry has been known to release large quantities of noxious gases which, in some cases, have been a detriment to the well being of the

livestock. The introduction of slatted floors also has resulted in facilitating the maintenance of more animals per unit of floor space. As a result, the moderate amounts of water vapour and noxious gases produced within the animals' immediate environment in less dense stocked systems may be increased to levels where they may adversely affect the livestock performance and health.

The question of atmospheric gaseous contamination in confinement units creates a dilemma for the agricultural engineer with regard to the design of a sound ventilation system. Data relating to the quantities of gases produced within a building under different manure handling systems for various classes of livestock and poultry under different feeding regimes are virtually non-existent. Again, information on threshold levels of the gases involved, when present singly or in combination, are very sparse. Early ventilation systems were designed primarily to maintain an acceptable carbon dioxide and ammonia level on the basis that the heavier gases accumulate near floor level and the lighter gases move upward from their point of generation. Recently, this theory has been discounted in that little stratification was found in a well ventilated facility since temperature gradients and air movement were found to be responsible for diffusing the gases fairly evenly throughout the room atmosphere. Once physiological data on moisture output of livestock and data relating to the evaporation of moisture from surfaces within a livestock building became available, water vapour removal and heat balance became the ventilation criteria for establishing minimum ventilation rates. With the introduction of slatted floors and storage pits constructed within the facility, manure gases may yet prove to be a major factor in establishing minimum ventilation rates. In

poultry houses, this problem of gaseous contaminants has been prevalent in some cases where restricted ventilation in winter was used as a means of conserving heat.

2. REVIEW OF LITERATURE

2.1 Moisture Production in Livestock Buildings.

Animals lose moisture by excretion in urine and faeces and by evaporation from skin and lungs. In total confinement livestock housing, the control of moisture as water vapour in the atmosphere is a prime function of ventilation. The production of water vapour within such a building is not only the result of moisture evaporation from the animals themselves but also arises from evaporation of moisture from various sources including floor surfaces, waterers and the animal wastes.

A measure of water vapour production within the building is the latent heat loss from the building. This heat loss in the form of water vapour may vary considerably depending upon management practices, building design, and effectiveness of the ventilation system (17). Although the moisture production of cattle was of prime interest in this experiment, that of swine and poultry were also considered in this literature review since more extensive research has been carried out in this area, especially in relation to their response to different thermal environmental conditions and building design.

The results of investigation in this area have been summarized and presented as recommended values for moisture production for cattle, pigs, and poultry in building codes and standards for ventilation design purposes (3,4). Such design criteria, however, have limitations in practice, being too generalized to meet all situations and because the data on which they are based has been limited.

Bond et al (12) developed a series of regression curves to provide a means of estimating the moisture that is required to be removed by the ventilation system in swine housing. This vapour removal was expressed

mathematically by the following regression equation:

$$Y = -0.961 + 0.291X_1 - 0.785X_2 - 0.146X_1X_2 - .029X_1^2 + 1.375X_2^2$$

where Y = logarithm to base 10 of moisture removal rate (lbs/(hr)(hog)),

X_1 = body weight/hog (lbs x 10^{-2}), and

X_2 = air temperature (^{o}Fx10^{-2}).

Harmon et al (27) measured the water vapour removal rate from hog houses with different types of flooring. Equations were developed by the least squares method for the moisture removed from each type of house. These equations were:

For the concrete floored house:

$$\log y = -0.434 - 1.71X + 1.89X^2$$

For the partially slotted floor house:

$$\log y = 0.0421 - 3.59X + 3.48X^2$$

For the slotted floor house:

$$\log y = 0.233 - 4.80X + 4.14X^2$$

where y = moisture vapour removal rate (lbs/(hog)(hr)), and

X = air temperature (^{o}Fx10^{-2}).

These researchers found that the regression equation developed by Bond et al (12) was useful in predicting the water vapour removal rate from concrete floors but the estimated values for the partially slatted or totally slatted floors were too high.

Driggers, cited by Winfield (57), indicated that one third of the moisture produced by a laying hen is respired. Moisture production of young broilers depends on the weight of the bird and the environmental temperature. Longhouse (40) carried out an extensive study in which he

developed a procedure to analyze a moisture balance within a poultry house.

Of the total amount of water consumed by an animal, a small percent is retained. Blaxter (9) stated that 70 per cent of the body weight of cattle consists of water, therefore, the amount retained by the animal is proportional to the gain in liveweight. Blaxter also noted that the respiratory loss of water accounts for 25 to 35 per cent of the total loss of water in cattle. Of this amount, 30 per cent is removed by the lungs while 70 per cent of the moisture is removed through the skin.

2.2 Factors Affecting Design Criteria for Ventilation in Confined Livestock Units.

Thermal environmental factors such as relative humidity and temperature are known to influence animal production. In order to control these factors, certain criteria are used to determine the ventilation requirements for a particular confinement unit. These are discussed below.

2.2.1

a) Outside Design Conditions

A variety of means have been proposed to establish an outside design temperature and relative humidity for winter and for summer. In winter, the use of minimum hourly outdoor dry bulb temperatures and relative humidities which have been equalled or exceeded 97 1/2 per cent of the total hours is a common practice in industrial and commercial practice and is recommended for total confinement livestock buildings by the American Society of Agricultural Engineers (3) in their current standards. The Canadian Code for Farm Buildings (4) recommends that the outside winter design temperature for ventilation should be determined on

a 5 per cent basis, that is, the temperature value expressed in degrees Fahrenheit at or below 5 per cent of the January hourly outdoor temperatures occurring. Longhouse (40) recommended that the mean monthly dry bulb temperature and relative humidity at noon be used for the coldest month. Esmay (21) proposed that the outside design temperature be the average of the temperatures for the coldest month.

Hot weather ventilation is usually based on the month of July since this is normally the hottest month. In order to determine the maximum hourly outdoor design dry bulb temperature and relative humidity for this period, the same procedure is used as for the winter outdoor design dry bulb temperature.

2.2.2 Inside Design Conditions

The inside design temperature is largely dependent on the type of livestock housed. Optimum temperatures and relative humidities have been recommended by many researchers (20,30,39,59). Several references have summarized this data (3,4). The degree of fluctuation between inside temperatures without drastically affecting production is also discussed by these investigators.

According to Prosser, as cited by Winfield (57), relative humidities of 45 to 75 per cent are acceptable to most livestock. The lower the relative humidity, the higher the mortality of disease organisms while, at a higher relative humidity, the heat produced by the livestock is more difficult to dissipate by respiration (32). At higher temperatures, relative humidity may have an adverse effect on animal production.

2.2.3 Livestock Density

The livestock density within a confinement unit is largely dependent on management practices, that is, selecting an optimum number

of animals without adversely affecting production. The number of animals also may be selected on the basis of reducing the amount of supplemental heat required (23). Because of the temperature extremes that occur between summer and winter conditions in Alberta, a compromise in stocking density must be made such that moisture produced within the building can be removed in the winter and excess heat removed in the summer by means of the ventilation system.

2.2.4 Heat and Moisture Removal From A Confined Livestock Unit.

Reece and Deaton (47) found that the total heat removed from a livestock unit during the summer months was in the same order as the total heat removed during the winter months. The difference that did occur was in the sensible to latent heat ratio. In winter, the production of sensible heat was a maximum while, in summer, the latent heat production was higher. The ratio of latent heat to total heat production may be affected by age, weight, condition and species, by ambient and mean radiant temperatures, and by plane of nutrition of the animals confined (23). The amount of moisture removed approaches the total water consumed as ambient temperature increases (10). The sensible to latent heat ratio of the animals was quite different from the ratio obtained from the confinement unit since some of the animal sensible heat was used to vaporize excess moisture on the floor (12).

Esmay et al (22) carried out extensive investigations to determine how evaporative cooling could be maximized, that is, minimizing the temperature rise of air moving through the house. In some cases, high outside temperature conditions appeared to bring about higher ratios of latent heat removal even when high outside relative humidities prevailed than at lower outside temperatures (22).

Reece and Deaton (47) discussed the advantage of night ventilation during the hot summer months since the outside temperatures are normally at a minimum at this time. They proposed that, because of the diurnal variation in temperatures, the usual daytime activity should be encouraged during the night by use of lighting. The authors also discovered the occurrence of a low sensible heat removal during the afternoon and suggested that this phenomenon could be due to the following factors:

a) A reduction in heat production of the animals since there was less activity and an adjustment in metabolism at this time.

b) Floor litter becoming in fact a heat sink at high temperatures with the release of heat as ambient temperatures fall as a result of decreasing outside temperatures.

c) The sensible heat being used to evaporate litter moisture during the afternoon when the lowest relative humidity existed.

On this basis, they suggested that the sensible heat production is not satisfactory as a ventilation criteria because of these variable conditions occurring.

2.2.5 Flooring Systems

Harmon et al (27) found that floor type of a hog finishing barn affected the quantity of moisture removed by the ventilation system. The water vapour removed from fully slatted-floor housing was 0.42 of that removed from a concrete-floored house. They also discovered that the moisture produced from a partially slatted floor was proportional to the percentage of the floor which was slatted. One shortcoming of their comparison of flooring systems was the fact that different relative humidities existed for each type of flooring system because of different

water vapour removal rates. A high relative humidity tends to reduce evaporation, thus the differences in the water vapour removal rate would decrease in significance. For finishing hogs on partially slatted floors, a ventilation system capable of 20.25 cubic feet per minute (cfm) per hog was recommended (44).

The effect of slatted floors on the air flow characteristics within a model confinement structure was studied by Shulte et al (49). They found that flooring schemes had little effect on air velocity when the incoming air was not baffled. Pit depth caused differences in the air velocities within the model. As the air was extracted above the slats, the air moving over the slats caused the air from the pit below the slatted floor to be drawn through the slats into the upper portion of the model. They also found that the distribution of regions of constant velocity was more uniform above a solid floor than a slatted floor.

2.2.6 Ventilation Criteria

Esmay et al (22) stated the importance of ventilation or exchange air being evenly distributed throughout the confinement unit in order to attain maximum drying and cooling of the house. Stapleton and Cox (50) found that the air should be removed at the most humid or wettest point in the building and that the air should be extracted opposite to the wall with the greatest glass exposure such that the warmer air might be drawn into the cooler areas to provide some additional heat.

Dick and Loader (17) found that the factors most responsible for the state of the internal climate of a fairly typical range of hog houses were attributable to the differences existing in the insulation and ventilation. Management practices seemed to play a minor role in the housing conditions. In their study, they expressed atmospheric moisture

content in two ways; (a) in terms of relative humidity which was the factor determining the equilibrium moisture content of materials such as bedding, and (b) as a saturation deficit which was the measure of the rate of evaporation of free water. Thus, a low relative humidity will ensure dry bedding and a high saturation deficit will ensure rapid drying of the floor. They found that an increase in the ventilation rate in a well insulated house dropped the relative humidity very quickly while, in the poorest insulated house in their studies, the relative humidity dropped very slowly. Also, as the ventilation rate was increased, a minimum relative humidity was reached after which it increased again with increasing ventilation rates. The same phenomenon occurred with the saturation deficit as ventilation rate was increased. In the best insulated house, the maximum saturation deficit occurred at a lower ventilation rate than in the poorest insulated house. They found that the maximum saturation deficit occurred at a lower ventilation rate than the minimum relative humidity for the same hog house.

The ventilation system in a well insulated house should be designed to remove the moisture as it is being produced by respiration and skin evaporation from the animals. The moisture in the droppings or litter may be removed during the better drying days (40). No information is available for determining or calculating the rate of evaporation from litter or dropping pits.

Some ventilation criteria,used in calculating the moisture removal rate,has been described by Longhouse (40). To calculate the amount of air required to remove one pound of water per hour, the outside and inside temperatures must be established along with the relative humidity, that is, the dry and wet bulb temperatures of the incoming and extracted air

must be known. The following equations are necessary to calculate the moisture removal.

$$e = p_w - \frac{(B-p_w)(t_d-t_w)}{2800 - 1.3t_w} \quad \text{(Carrier's Equation)} \; . \; . \; . \; . \; . \; . \; . \; (1)$$

where e = partial pressure of the vapour in air (in. Mercury (Hg)),

B = barometric pressure (in. Hg),

p_w = the vapour pressure of water at the wet bulb temperature, (in. Hg),

t_d = the dry bulb temperature (^oF), and

t_w = the wet bulb temperature (^oF).

$$W = \frac{4360p_w}{B - p_w} \; . \; (2)$$

where W = grains of moisture per lb dry air, and

e = partial pressure of vapour in air (in. Hg).

$$V = 0.754 \frac{(t_d+459.7)}{B} \quad 1 + \frac{W}{4360} \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; (3)$$

where V = specific volume of one pound of air (ft^3 per lb dry air),

t_d = dry bulb temperature (^oF),

B = barometric pressure (in. Hg), and

W = grains of moisture per lb of dry air.

The heat removed by the exchange air can be calculated from the following equations,

$$h = h_{ae} - h_{al} \; . \; (4)$$

where h = heat removed by one lb of exchange air (BTU's),

h_{ae} = enthalpy of one lb of dry exhaust air (BTU), and

h_{al} = enthalpy of one lb of incoming dry air (BTU).

$$h_a = C_p(t) + \frac{W}{7000}(1061.7+.439t). \ldots \ldots \ldots \ldots (5)$$

where h_a = enthalpy of one lb of dry air (BTU),

C_p = specific heat of air at constant pressure (BTU per lb., ^oF),

t = dry bulb temperature (^oF), and

W = grains of water vapour per pound of dry air.

The conductance heat losses of the house and the total heat produced also must be determined in order to establish the heat available to warm the incoming air such that the moisture may be removed and the desired indoor temperature maintained (40,20,23). If insufficient heat is available to remove the moisture at a desired temperature, the following alternatives may be considered; (a) the housing density may be increased, (b) additional insulation added to the structure, or (c) additional supplemental heat may be provided to the confinement unit (20). Other alternatives used to conserve heat might include lowering the desired temperature or the ventilation rate (20,23).

2.3 Environmental Requirements of Livestock.

Environmental requirements with respect to temperature, relative humidity, gases, ventilation, dust, space, and pathogenic organisms have not been investigated to a large extent. Hicks (32) emphasized the fact that the interactions of all the environmental factors must be studied more extensively. He also pointed out that a close control of all the environmental factors is required before an accurate assessment can be made as to the reaction of livestock to their environmental stimuli. The ranges that may be tolerated by the animal before its production is adversely affected must also be studied more extensively (32). Live-

stock can acclimatize within broad ranges to various stimuli. Therefore, the total influence of the environmental factors would depend largely on their intensity and the interaction of other stimuli.

Mangold et al, cited by Gunnarson (26), stated that no significant differences occurred in rates of gain and feed conversion ratios between temperatures of 50°F and 75°F for growing-finishing swine. Heitman et al (30) found that, for 100 lb growing hogs subjected to relative humidity of 50 per cent and air velocity of 25 feet per min., the optimum temperature at which the rate of gain was maximum was 74.5°F. According to Dukes (18) the upper critical temperature of a chicken is approximately 81°F. With dairy cows, Yeck (59) found the best production occurs at temperatures between 45°F and 65°F. Relative humidity effects are insignificant at this temperature range except for higher temperatures. In their investigations, Heitman et al (30) found that the maximum daily gains varied from 61°F for 350 lb hogs to 73.5°F for 100 lb hogs. The optimum temperature of beef cattle varies with breed, age, weight, and condition (36). Factors affecting the proportion of total heat lost as vapour are age,weight, condition, breed of animal, ambient temperature, relative humidity, air motion, and plane of nutrition (23). Several references have summarized the environmental requirements of livestock (3,4).

Cloud, cited by Winfield (57), suggested a maximum of 80 per cent relative humidity for laying hens. Hazen and Mongold (28) stated that humidity had little effect on growth efficiency unless accompanied by thermal stress. They were informed by producers that high humidities brought good success with growing swine. The growth of disease organisms and deterioration of the building and equipment is not well known. At a

high humidity level, less supplemental heat and ventilation are required, in which case odour production may become a limiting factor.

2.4 Physiological Effects of Relative Humidity and Temperature on Livestock.

Mueller, cited by Winfield (57), found that pullets kept in an environment where the temperature cycled from $55^{o}F$ to $90^{o}F$ and back to $55^{o}F$ every 24 hours, produced more eggs than the pullets kept at a constant temperature of $55^{o}F$. The need to avoid low temperatures was noted by Baxter (6) because of the extra energy expended for body temperature maintenance. At higher temperatures, a loss of appetite occurs since there is an increase in energy requirement for dissipating the heat (6). Hicks (32) stated the difficulty that exists in defining thermal stress because of the interactions between relative humidity and temperature and between air movement and temperature. Heitman (30) found that small ambient temperature changes may lead to large changes in the environment. Pig losses, poor weight gains and low food consumption were always problems among pigs reared in an uncontrolled environment or a large insulated building (12). Studies carried out on the effects of elevated temperatures on pregnant sows indicated that feed and water consumption decreased and the sows lost weight, but the majority of the pregnant sows farrowed successfully after the period of high temperature (11,29).

Relative humidity was found to be very critical in chicks (39). Young broilers could sense a 5 per cent change in relative humidity from the comfortable level of approximately 50 per cent. Also, if the temperature was significantly higher or lower than $75^{o}F$, the birds were uncomfortable and consumed more feed per pound gain. At higher temperatures, relative humidity had very little effect on feed consumption

and growth.

2.5 Noxious Gases Produced by Stored Livestock Wastes.

Storage of wastes within a confined unit in the form of liquid manure beneath a slatted floor for long periods of time has become a fairly common practice. As a result, noxious gas production is a serious problem and toxic levels have been reported (45). The gases released and their quantities are directly related to the type of bacteriological decomposition which occurs in the waste. The decomposition may be aerobic or anaerobic in nature.

2.5.1 Anaerobic Treatment of Livestock Wastes

Anaerobic decomposition is the most common process found in stored livestock wastes. This process takes place in the absence of dissolved oxygen. In this environment, the chemically bound oxygen in the organic matter is used by the anaerobic or facultative anaerobic organisms (15, 45). The oxygen may be bound with sulphur as sulphate ions, with nitrogen as nitrate ions, with carbon and hydrogen in various organic compounds or with carbon alone as carbon dioxide.

Most of the complex organic compounds are hydrolyzed or broken down to simpler compounds by extracellular enzymes such that they become available to the bacteria. This process is referred to as the liquifaction phase (45). Therefore, the initial products of anaerobic decomposition are organic acids, acid carbonates, carbon dioxide and hydrogen sulphide. This acid production leads to a drop in pH. At the end of the acid phase, the decomposition of organic acids and soluble nitrogenous compounds occurs which results in a rise of pH (6). The products of this stage are ammonia nitrogen, acid carbonates, carbon dioxide and sulphides. At this point, bacterial growth becomes more

favourable due to a rising pH (15). This rise in pH introduces the methane stage or the alkaline fermentation phase. Methanogenic bacteria are responsible for the final products of decomposition which include ammonia nitrogen, humus, carbon dioxide, methane and sulphides. These bacteria are strict anaerobes. Little is known of these specific microorganisms (45).

Temperature exerts a great effect on anaerobic digestion. Basically, there are two temperature ranges in which anaerobic decomposition takes place. The mesophilic range extends up to 110^{o}F with its optimum range being 95-100^{o}F. A higher temperature range, known as the thermophilic range, has a temperature range of 110-149^{o}F. Its optimum temperature is 130^{o}F. The anaerobic process at the thermophilic range is more rapid but is uncommon since additional heat is required and the process is more difficult to operate.

With respect to gas production, Clark and Viesman (15) state that, in domestic sewage, the Methane (CH_4):Carbon Dioxide (CO_2) ratio is 7:3 with trace amounts of hydrogen sulphide (H_2S), ammonia (NH_3), hydrogen (H_2) and nitrogen (N_2) gas being generated. Muehling (45) states that, depending on existing conditions, CH_4 production in wastes constitutes between 60 and 80 per cent of the total gas production. The remainder of the gases evolving from the slurry is CO_2 with 1 per cent being comprised of intermediate products such as H_2S, NH_3, H_2 and N_2. These intermediate products are responsible for the odour associated with the anaerobic process.

Clark and Viesman (15) indicated that one pound of volatile matter will produce 16-18 litres of gas. Hobson, cited by Baxter (6), carried out an analysis on pig slurry in its natural anaerobic form in which he

found that 11 litres of slurry produced 17 litres of gas between the fifth and ninth day of degradation. By the nineteenth day, only small amounts of gas were being produced. The analysis of the gas indicated: 17 per cent CH_4, 82 per cent CO_2 and 1 per cent H_2S. The ratio of CH_4 to CO_2 thus differs from that suggested by Clark and Viesman (15). This difference was explained by Baxter (6) who noted that uncontrolled anaerobic digestion would appear to only reach the liquefaction, or at the most, the acid stage. Carbon dioxide generated from hog waste has been measured at 0.66 cubic feet per hour per 100 lb. hog while ammonia has been measured at 0.189 cubic ft per hour per hog (6).

The major advantage of anaerobic decomposition is its great capability to break down organic matter. Loehr, cited by Muehling (45), stated that the usual purpose of anaerobic lagoon is the destruction and stabilization of organic matter rather than water purification. Another advantage is that, as a controlled process, it produces large amounts of CH_4 which can be used as fuel. Anaerobic decomposition also can serve as a pretreatment to aerobic systems because of its high organic removal rate.

2.5.2 Aerobic Treatment of Livestock Wastes.

Aerobic decomposition is the reduction of organic matter by aerobic microorganisms which require free oxygen or dissolved oxygen to exist. These bacteria use waste as a substrate, breaking down part of the organic portion into more basic compounds such as water and carbon dioxide. Most of the nitrogen is converted into nitrates and nitrites with some being released to the atmosphere as N_2 and NH_3-N. The H_2S is converted to sulphur, then finally to sulphates (45). Organic phosphorus is converted to phosphates. The only gas produced to any large extent is CO_2 and most of this stays in solution as bicarbonate. Organic matter

not oxidized to CO_2 and H_2O was converted to stable solids (34). Aerobic treatment is less efficient than anaerobic in that only 40 to 50 per cent degradation of volatile solids occurs.

Dale, cited by Muehling (45), suggested four distinct advantages of aerobic decomposition:

1. Partial decomposition of organic solids into odourless gases.
2. Destruction of most of the pathogenic organisms.
3. Reduction of pollutional characteristics of the wastes.
4. Concentration of minerals which may be more readily applied to the land.

2.5.2.1 <u>Methods of Aerobic Treatment</u>

Muehling (45) describes two methods of treating livestock wastes by aerobic decomposition. These are natural aerobic lagoons and mechanically aerated lagoons or oxidation ditches.

1. Naturally aerobic lagoons.

   These consist of a shallow basin three to four feet deep. Purification occurs under climatic conditions which produce algae growth. This process entails a symbiotic relationship between two major groups of microorganisms - the bacteria and the algae. Rich (48) states that the bacteria utilize organic waste materials for growth and energy. The CO_2 and NH_3 released by hydrolysis is utilized by the algae (photosynthesis). Oxygen is produced by this process which makes possible further bacterial oxidation (48). The feasibility of this process is debatable in areas with long winters.

2. Mechanically aerated lagoons and oxidation ditches.

   The principles of the operation of mechanically aerated lagoons

and the oxidation ditch are essentially the same other than the means of storage and the type of agitator used. Some advantages of a mechanical aerated lagoon over oxidation ditches, as listed by Dale, and cited by Muehling (45), are:

1. A larger volume of wastes may be handled with a lower initial cost, thus a longer detention time can be utilized.
2. If equipment should break down, the event of anaerobic decomposition occurring with its associated odours would be outside the confined unit.
3. Less aeration or free oxygen is likely required.

Some of the disadvantages (45) of a mechanically aerated lagoon are:

"1. It is subject to freezing.
2. It may be unsightly;
3. It requires more space than the oxidation ditch."

The oxidation ditch is a continuous open-channel ditch in the form of a race track. A common location of the oxidation ditch is below the slatted floor. The liquid wastes can be deposited in the ditch by way of the slatted floor or pumped to an oxidation ditch located outside the confinement unit from a storage pit within the housing facility. A rotor or agitator introduces oxygen to the aerobic environment and, in addition, keeps the solids in suspension as they are being circulated around the ditch.

The Midwest Plan Service (60) list the following advantages of the oxidation ditch:

1. Decrease in odours during storage and disposal.

2. Ditch and equipment operation and maintenance is relatively simple.

Several disadvantages are also noted:

1. An increase in cost for the equipment and facilities.
2. If the ditch is underdesigned, foaming and odour problems may occur.
3. If the rotors break down, immediate attention is required to ensure that anaerobic decomposition will not take place.
4. Installation of a ditch into an existing building is very difficult and would require major reconstruction.

2.6 Noxious Gases Existing in Confinement Livestock Buildings.

Noxious gas production with a livestock unit may be either from the livestock, the animal wastes, or from both sources. The animal wastes may be in litter form or as a liquid beneath a slatted floor.

Extensive research has indicated that CO_2 and CH_4 are the only gases produced in significant quantities by the livestock as a result of their metabolic processes. It was found that an average ruminant produces 1 litre CH_4 per 10 litres CO_2. At low ventilation rates, an accumulation of CO_2 stimulates the respiration of the animal. Thus, the amount of CO_2 expired by the animal may vary to a large extent (6). Also, variations may be brought about by the nature of foodstuff being oxidized (18). It would seem that, to accurately measure the CO_2 expired, a carbon dioxide balance must be carried out on the animal since the quantity of CO_2 expired varies with type and breed of animal, plane of nutrition, the liveweight gain and activity of the animal. Dukes (18) cited evidence that a highly fed dairy cow may produce up to 300 litres of CO_2 by fermentation in a day. Baxter (6) also cited evidence that

the quantity of CO_2 expired by pigs increased with liveweight, activity and level of nutrition and with decreasing environmental temperatures. Methane is found in considerable amounts in the expired air from herbivores derived from carbohydrate fermentation in the alimentary canal. Most of this gas is eructed from the animal at irregular intervals. Cattle may produce up to 400 litres per day per animal while the production of methane may approach 50 litres per day (9).

Several investigators have studied extensively the noxious gases prevalent in confined livestock units. Peterson, cited by Longhouse et al (41), stated that 13 to 55 cubic feet of CO_2 per hour per 1000 broilers were produced at 3 lb liveweight. A swine barn, ventilated at 35 cfm per hog, with slatted floors above an anaerobic pit had concentrations of 7.4 parts per million (ppm) of NH_3, 656.6 ppm of CO_2 and 0.026 ppm H_2S. When the ventilation system was not functioning for 6 hours ,the threshold limit of the gases was not reached (38). Taiganides and White (54) reported cases of death caused from inhaling air devoid of oxygen. These deaths occurred when the slurry was agitated, thus releasing the CO_2 which was trapped by the scum on the slurry. Hydrogen sulphide is also reported to be released in large quantities after agitation of the slurry (16,42).

Longhouse and Ota (39) note that, in poultry houses using fuel-fired brooding and heating equipment which do not exhaust combustion products, very high and moderate amounts of CO_2 have been observed at bird level. High CO_2 concentrations of 5000-6000 ppm have been observed in commercial poultry houses. According to Hiestand, cited by Longhouse et al (41), chickens can withstand up to 60,000 ppm. At a CO_2 level of 10 per cent ,only an increase in amplitude occurs but no increase in

breathing is apparent.

Valentine (56) indicated that, in three to five weeks after introducing fresh litter, NH_3 was detected. Also, if the litter contained more than 28 per cent moisture or the dry matter to fecal dry matter ratio exceeded 1.94:1, NH_3 gas production began. Hammond, cited by Baxter (6) found that, at 20 cfm per hog and air temperature of 86°F, the NH_3 concentrations ranged from 15-21 ppm at a floor temperature of 104°F. When the floor temperature was reduced to 79°F, the NH_3 concentration decreased to approximately 7 ppm. With an ambient temperature increase of 55°F to 80°F, the NH_3 production almost doubled (28).

2.7 Physiological Effects of Noxious Gases on Livestock.

There have been several studies (6,33,52,54) on the physiological effects of noxious gases on livestock. The effects of the more important gases are discussed below.

2.7.1 Carbon Dioxide

This is a colourless, odourless gas which is heavier than air and soluble in water. It has been found that the upper limits range from 7 to 10 per cent of the exchange air (54). Baxter (6) stated that CO_2 is simply an asphyxiant such that it will cause death by depriving the animal of oxygen. In poultry, it was found that at 5000 ppm there was an appearance of distress, depressed appetite and reduced shell thickness (31).

2.7.2 Methane

This gas is similar to CO_2 in that it is an asphyxiant at high concentrations. Being highly flammable, methane will ignite at 5 per cent by volume (54). It differs from CO_2 in that it is lighter than air.

Since it is very insoluble, it escapes readily into the air. The concentrations of methane are usually lower than CO_2 depending on the degree of the anaerobic treatment of the slurry. For optimum CH_4 production, the liquid manure must be heated between 90-100°F (54).

2.7.3 Ammonia

Ammonia is an irritant gas and has a pungent odour. Being very soluble, it is retained in solution to a large extent. For this reason, greater concentrations of ammonia have been found in deep litter or solid floor systems than in slatted floor systems (45,54). Different types of litters generate different quantities of NH_3. In poultry, the NH_3 level should be kept below 20 ppm since, at higher concentrations, they developed ulceration of the conjunctiva or became prone to respiration diseases such as Newcastle disease (56). At levels of 100-200 ppm, anorexia (lack of appetite) was reported by Baxter (6). In hogs, no apparent problems were presented at concentrations ranging from 50-100 ppm (6) whereas Stombaugh (52) found that NH_3 concentrations within the range of 12 and 145 ppm significantly affected feed consumption and average daily gain. There was no significant effect upon efficiency of feed conversion. Hogsved and Holtenious (33) indicated that, moderate concentrations may not be lethal in themselves but that a combination of NH_3 and H_2S would be more detrimental to animal health and performance than H_2S alone.

2.7.4 Hydrogen Sulphide

Hydrogen sulphide is produced from decomposition of organic wastes under anaerobic conditions. Baxter (6) states that the threshold limit of H_2S is 20 ppm. At higher concentrations, a loss of appetite, nervousness and fear of light develops along with a chemical reaction with blood and tissues (6,54). Most of the investigators were in

agreement that the concentrations were usually well below 20 ppm except in the cases where liquid manure beneath the slatted floors was agitated. At higher concentrations, there may be no ill effects but the animals can become susceptible to pneumonia and other respiratory diseases.

2.8 Distribution of Noxious Gases in Farm Buildings.

Until recently, the concept of gases heavier than air accumulating near floor level and gases lighter than air accumulating at ceiling level has been used as a criterion in designing ventilation systems. Taiganides and White (54) stated that CO_2 and H_2S, being heavier than air, accumulate at floor level while NH_3 and CH_4, being lighter than air, tend to move upwards from the point of generation. The King system of ventilation was designed as a gravity system for natural ventilation in which the outside air was introduced at or near the ceiling and the foul air was removed at floor level via a vertical flue (37,58). The claimed advantage of the system was the removal of the heavier CO_2 from floor level and retention of the warm air. The Rutherford system removed the air at the ceiling and introduced the air at floor level (58). More recently, the Cornell ventilation system was designed to extract the environmental air near the ceiling in summer and at floor level in winter (55). This arrangement was considered to remove the excess CO_2 in winter when ventilation rates were low and remove excess NH_3 in summer when NH_3 production was at a maximum.

Recently, Noren et al (46) reported, however, that gases did not accumulate at levels depending on their densities. They found that the concentrations of heavier gases such as CO_2 and H_2S were the same or higher at ceiling level than at floor level. The NH_3 levels also were

found to be equally diffused throughout the building except below slatted floors where concentrations were higher. It also was observed in hog and cattle facilities that upward air currents from gutters occurred where the animals were located (46). This was due to the heat production of the animals. Brannigan and McQuitty (14) substantiated these results in controlled experiments and also reported that sensible heat is the major factor in the diffusion of gases in the atmosphere.

Schulte (49) reported that air from below a slatted floor either is drawn up through the slots into the livestock unit due to air passing over the floor, thus creating a partial vacuum at the slats, or is forced through the slots by ventilating air entering the pit air space at some point. In practice, factors responsible for determining the movement of gases from their point of generation are: a) temperature gradients creating convection currents, b) air movement as a result of forced ventilation and c) molecular diffusion due to concentration gradients (Fick's Law) of gases. Brannigan (13) found that Fick's Law of Gaseous Diffusion had a negligible effect on gas diffusion relative to air movement and temperature gradient.

3. OBJECTIVES

Presently the trend in livestock production is toward fewer, larger, and more specialized types of confinement in an effort to reduce production costs, increase the number of animals per unit area and improve the quality of the product. Since these facilities normally are insulated and enclosed, some means of environmental control must be utilized to optimize management and efficiency. Also within these confined facilities, manure handling systems have been changing rapidly in that slatted floors are becoming more prevalent. Manure storage within these facilities have added another dimension to environmental control considerations, that is, the noxious gas production resulting from the decomposition of the stored wastes.

Ventilation of these facilities must ensure that the vaporized moisture and the noxious gases are removed so that their detrimental effects are minimized. The question then arises as to where or at what location the water vapour and gases are removed most effectively.

Therefore, the following objectives were considered in this research project:

(1) to determine the effects of confinement systems on the mean removal rates of water vapour and noxious gases (NH_3 and CO_2),

(2) to determine the effect of exhaust levels on the mean water vapour and noxious gas removal rates,

(3) to determine a moisture balance for each housing treatment and the proportions of their moisture input removed by ventilation,

(4) to determine the effect of aeration beneath a slatted floor on the mean removal rates of water vapour and noxious gases, and

(5) to determine the effect of different ventilation rates on the mean water vapour removal rates in a straw-bedded housing system.

4. EXPERIMENTAL PROCEDURE

4.1 Materials.

4.1.1 Livestock Environmental Engineering Laboratory.

This study was conducted from December 1, 1970 to April 31, 1971, at the Livestock Environmental Engineering Laboratory located at the Agricultural Engineering Research Station at Ellerslie, near Edmonton, Alberta. This 100 feet long by 40 feet wide facility is an insulated structure with an animal weigh room and a feed room located at opposite ends. The building is oriented with its long axis in a north-south direction. The livestock area, 80 feet by 40 feet, is fully slatted with 4 1/2 inch wide individual precast concrete slats 10 feet in length. The slats were spaced 1 1/2 inches apart throughout the period of this experiment. The slats are supported by the pit walls, the pits being situated across the building. Eight equal sized pits, each approximately 40 feet long by 10 feet wide by eight feet deep, are located beneath the slatted floor area. Two of these pits contained rotors or agitators to aerate the liquid wastes on the oxidation ditch principle. The first pit was equipped with one rotor and the second pit with two rotors. The remaining pits provided a storage function only for the liquid wastes; thus they were essentially anaerobic in nature.

The external walls of the building are 14 feet 4 inches from slat level to the wall plates and are constructed from 8 inch concrete-filled block consisting of 2 inch outer skins of cement-bonded wood fibre. The partition walls separating the feed and the weigh rooms from the livestock facilities are of standard stud construction with plywood sheathing on each face.

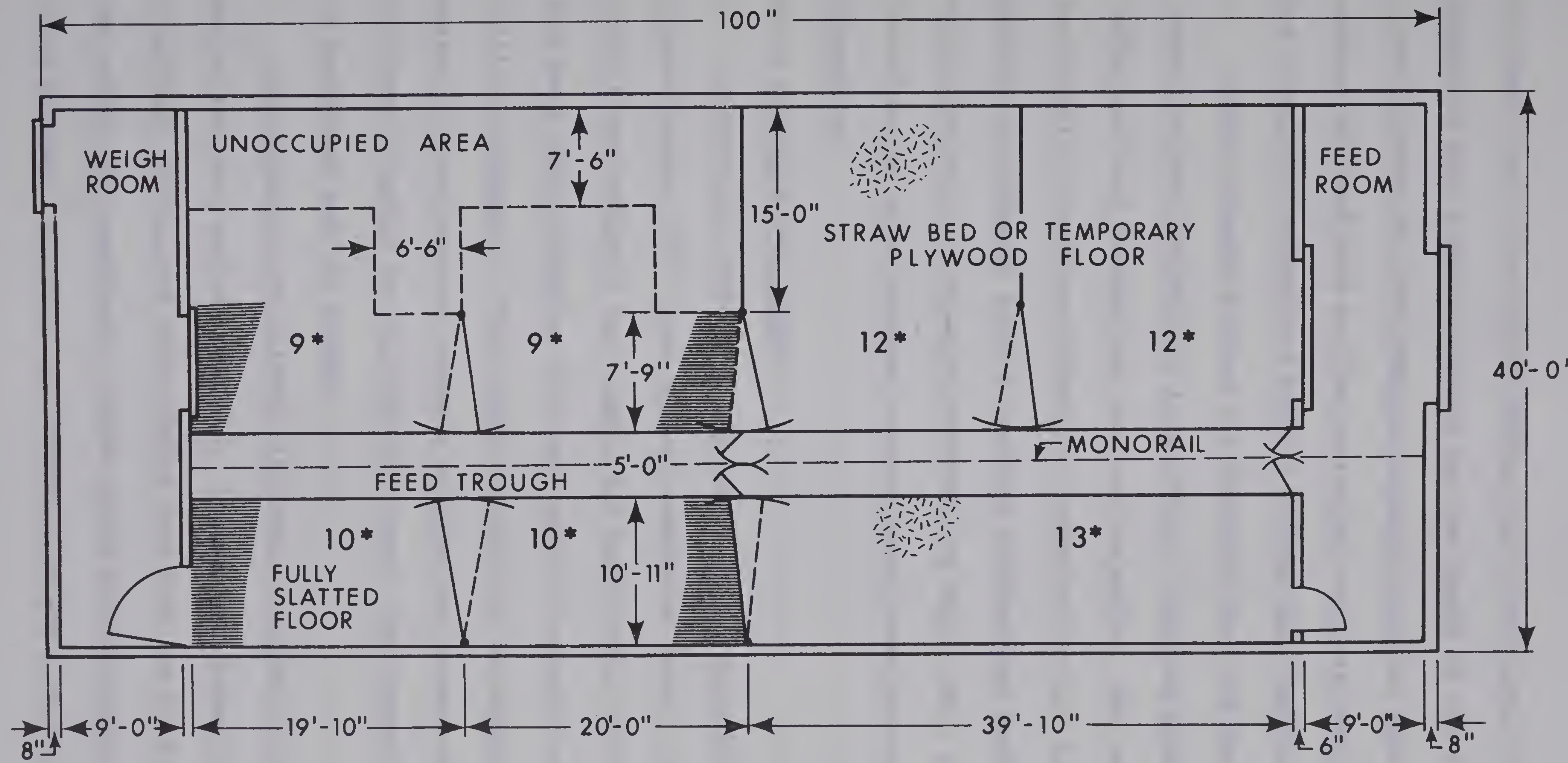
The gable type roof with a slope of 1:12 consists of three inch

rigid insulation on a polyethylene vapour barrier over 20 guage corrugated steel decking and is finished externally with standard built-up roofing. The roof is supported by shallow steel lattice trusses 10 feet o.c., providing, from its lowest horizontal member, a clearance of 11 feet and 8 inches above slat level.

For the purposes of the experiment, the livestock section of this facility was divided into two parts such that one half of the building contained a fully slatted floor area and the other half a straw-bedded area. The 'solid floor' for the straw-bedded area was achieved by laying 3/4 inch sheathing grade plywood sheeting over the slats. As the plywood became damp from the manure, it swelled such that a very minimal amount of moisture penetrated the floor and deposited into the collection pits beneath.

The housing systems were isolated from each other. A thorough attempt was made to seal each confinement unit so that all the ventilation air would be exchanged via the ventilation system. To isolate the two housing systems, a sealed partition was constructed across the building at the midpoint of the livestock area directly above the centre pit wall. This partition was constructed from masonite and two inch by four inch studs such that it covered the entire area between the roof and the slatted floor. Foam rubber was used to seal the gaps between the slats at the junction between the partition and the pit wall with the object of eliminating any air exchange between the two areas at this point.

To provide access for the cattle in the straw-bedded housing system to the weigh room, doors were constructed on each side of the feed bunk (figure 1). These were sealed with foam rubber. Sealed access doorways also were provided through the central partition and the wall adjoining



* - NUMBER OF ANIMALS IN EACH PEN
FULLY SLATTED FLOOR -25 SQUARE FEET PER ANIMAL
STRAW BEDDED FLOOR -36 SQUARE FEET PER ANIMAL

Figure 1. Floor plan of the Environmental Laboratory showing the pen layout within both housing systems.

the feed room to facilitate feeding via a feed-cart. The feed-cart was supported from a monorail which ran the length of the livestock unit directly above the feed bunk and extended into the feed room. The area between the feed bunk and the center pit wall was also sealed such that the partition between the housing systems was complete.

Doors situated between the livestock area and the feed and weigh rooms also were sealed with foam rubber. Caulking compound and foam rubber was used between the roof and the walls. The entire area enclosing each housing system was thoroughly inspected for air leaks and, if they existed, an adhesive tape or caulking compound was applied. Air leaks, which were not obvious,were determined by smoke tests using titanium tetrachloride which produces copious white fumes upon exposure to the atmosphere.

4.1.2 Livestock Pen Layout.

Seventy six feeder steers, predominantly Hereford, were purchased in mid-October, 1970, from a local commission agent. The animals on arrival were weighed, ear tagged, and ranked from lightest to heaviest. They were then divided so that each group of animals had a similar total initial liveweight. Thirty-eight steers were allocated to each housing system. Three groups of animals occupied the straw-bedded housing while four pens occupied the slatted-floor area. The average initial weight of each steer was 535 pounds.

The animals were allowed six weeks to adjust to their environment before the test period commenced. During this period, one steer died from bloat leaving the straw-bedded area with one less animal. Towards the end of the experiment, another steer died from bloat in the slatted-floor housing. An animal of comparable weight from the other housing

system replaced it as gas monitoring had been completed in the straw-bedded housing system at that time.

The pen layout, pen dimensions and number of animals in each housing treatment are shown in figure 1. The stocking density in the straw-bedded area was approximately 36 square feet per animal housed. The normal recommendation in commercial practice is around 55 square feet per 1000 lb liveweight (4,5). The actual space allowances were regarded as compatible with the weight ranges of the steers involved in the experiments and with the desire to ensure that the measurements of the parameters under study were within the optimum sensitivity ranges of the instrumentation available.

On the fully slatted-floor, the space per animal was approximately 25 square feet which is in accordance with the requirements of a 1000 lb steer (4). As shown in figure 1, the entire slatted-floor area was not utilized by the cattle since they required less space than the animals on the solid floor. The trough space per animal averaged 2.1 feet on the slatted-floor and 2.2 feet on the solid floor system.

4.1.3 Ventilation System.

Ventilation of the facility is by means of a pressurized system in which the air is drawn from the outside and forced through ducts into the livestock area by centrifugal fans. Rectangular galvanized steel ductwork runs from either gable of the building down the center of the building and extends to within three feet of the central partition which divides the two housing systems. Air is distributed into each livestock area from the inlet duct via diffusers fitted with volume dampers which permit balancing of the system. The ductwork is supported by the bottom members of the trusses. Each system is identical with the other and

incorporates a fan capable of delivering 4000 cubic feet per minute and a direct, gas-fired induct heater with a maximum rated output of approximately 250,000 BTU per hour.

For the purposes of the experiment, each fan capacity was set at 3000 cubic feet per minute. During the last half of the experiment the fan capacity for the straw-bedded housing system was changed back to 4000 cubic feet per minute. The capacity of 3000 cubic feet per minute was selected since it was the maximum ventilation that could occur at an outside temperature of -25°F, that is, the furnace was operating at its maximum rated output and maintaining a room temperature of 60°F. It was found that when the temperatures did fall below -25°F, the room temperature fell approximately 5°F from the normal room temperature of 60°F. This ambient temperature for each housing system was maintained since lower ambient temperatures were difficult to obtain when the outside temperature was greater than 30°F. The reason for this was that the minimal heat output of the induct heater plus the sensible heat from the animals would maintain a temperature of approximately 60°F. Therefore, to compromise for the fluctuating outside temperatures occurring during the Edmonton winter, it was felt that 60°F should be the desirable ambient temperature for the experiment.

For the purpose of the experiment, exhaust ducts were constructed at two levels as illustrated in figures 2 and 3. The upper ducts were positioned 6.5 feet above floor level and 6 inches from the external walls on both sides of the building. Each upper exhaust duct ran from the central partition along the outside wall to the partition wall which divided the livestock area from either the feed room or the weigh room (figures 3 and 5). This height was chosen since it is a common commercial

practice to exhaust air 6-7 feet from floor level. Avoidance of any interference from the cattle also was a factor influencing this decision. The lower ducts exhausted the air from immediately below the floor level (figure 3).

The exhaust ducts from each housing treatment were brought to a central location at both ends of the building to permit monitoring of all exhaust air before it escaped to the outside atmosphere. In the straw-bedded housing system, the duct which connected the two upper level exhaust ducts ran across the building along the inside of the partition wall which separates the feed room from the livestock area. This duct also served as a common duct for the lower exhaust level as well (figure 2). In the south east corner of this livestock area, the stale air left via the outlet duct which connected the upper exhaust duct running along the end wall and the common duct.

In the slatted-floor housing treatment, a similar design was used in exhausting the air through the upper ducts. In this case, both exhaust ducts were extended through the partition wall such that the common duct connected them in the weigh room (figure 2). From this common duct, the air was then exhausted from the building by means of an outlet duct, where the gases and moisture were monitored.

Each upper exhaust duct in each housing system was identical in that each duct had 8 evenly spaced 4 inch by 18 inch slots. These slots were comparable to the ventilation slots existing for low level exhausting (figure 3). At the time of the construction of the building, ventilation slots were constructed into the concrete walls of the pits along both sides of the building immediately below slat level in the livestock area. It must be noted that these lower exhaust ventilation slots are located

below grade level and were protected by 3 feet by 3 feet by 2 feet deep wells constructed from corrugated sheet metal. For the purposes of the experiment, the air was collected from each of these slots by a duct which ran along the outside wall from the center of the building to a location where it entered the building to continue in the common duct on to the outlet duct (figure 4). The lower exhaust duct for the east side of the straw-bedded housing system entered the feed room where it was joined to the outlet duct. Adaptors were constructed to divert the air from the slots to the duct.

In order to prevent the temperature of the air passing through these external ducts from falling such that condensation resulted, the ducts were covered with 2 inch glass fibre batt insulation protected by polyethylene sheeting from rain and snow (figure 4). The insulation proved very satisfactory since the relative humidities where the moisture was monitored did not exceed 90 per cent when the coldest outside temperatures occurred. These external ducts also were thoroughly sealed to ensure no air escaped before it was monitored in the outlet duct of each housing system.

To ensure that only one exhaust level was in operation at a time, provision was made to permit wooden plates to be inserted or taken out at the end of each exhaust duct, depending on the set of ducts being used to exhaust the room air. The outer edge of these wooden plates were covered with weather stripping such that, when the plate was seated against a wooden framework within the duct, a very satisfactory seal was obtained.

The sizing of the ducts was based primarily on the desirable velocity of the air flowing over the wet-bulb thermocouples placed in

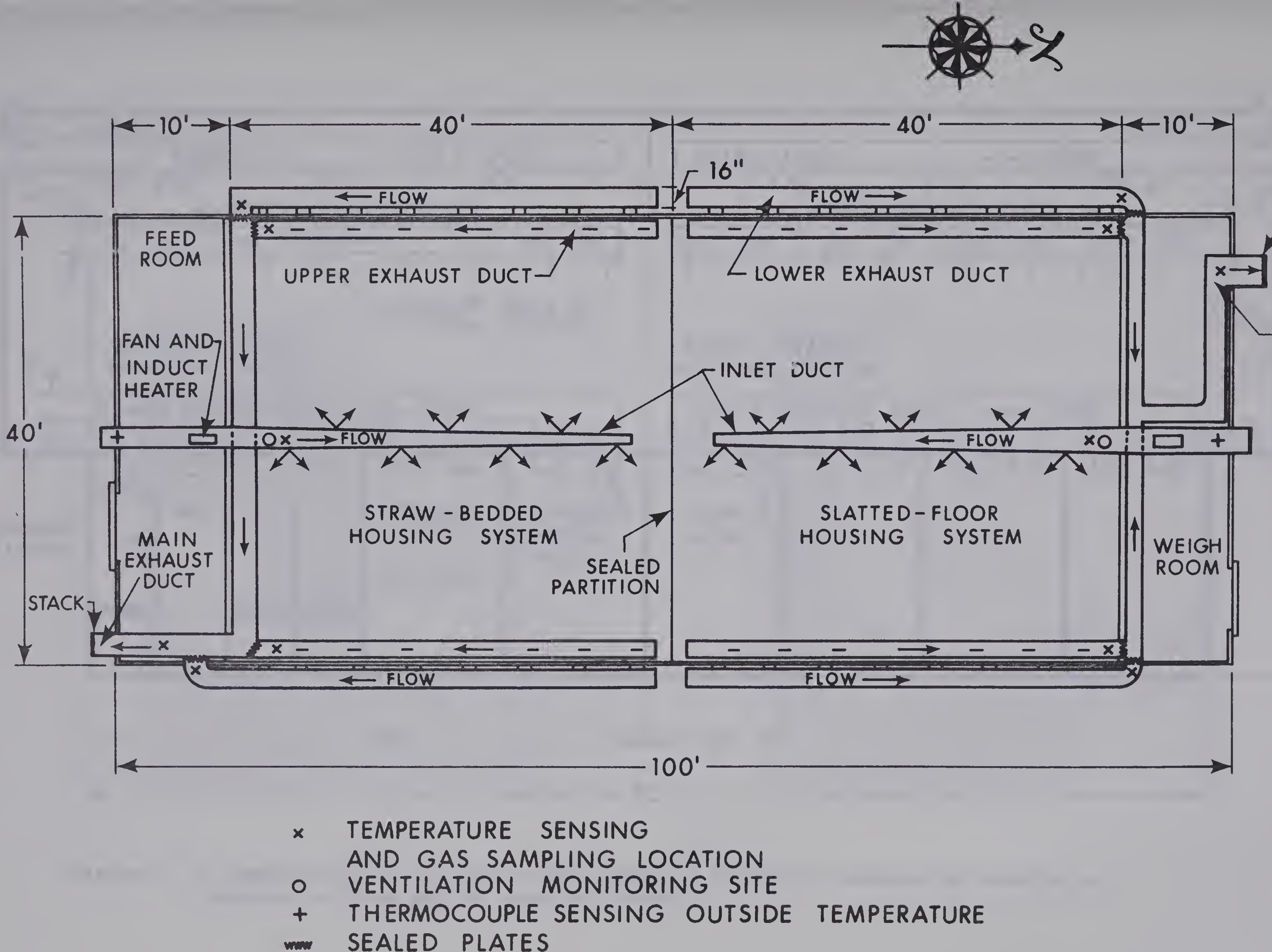


Figure 2. The location of the inlet and exhaust duct systems and the monitoring sites within each housing system.

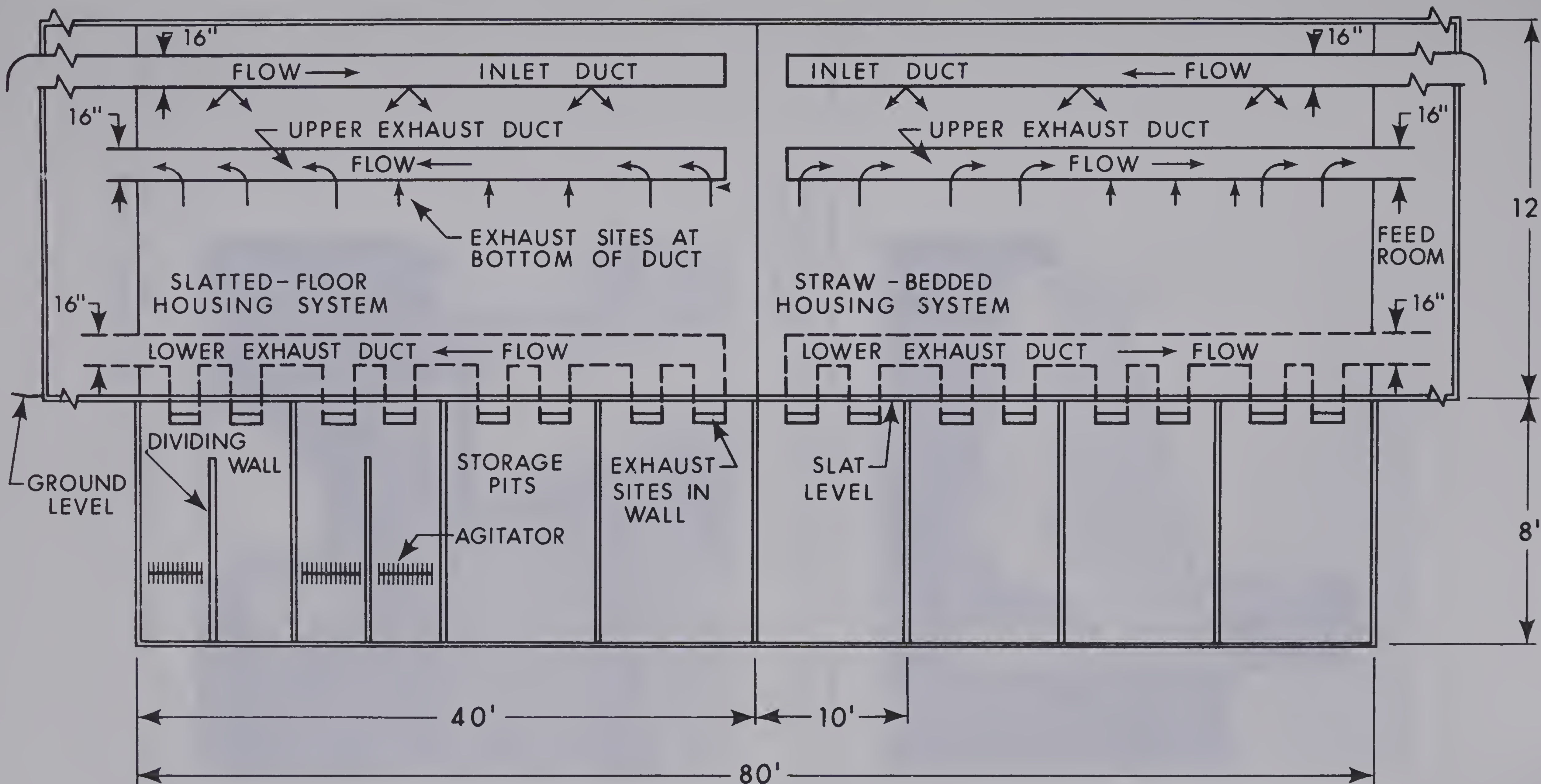


Figure 3. A longitudinal section of the Environmental Laboratory showing the location of ventilation ducts and the aeration rotors.

Figure 4. External insulated ducts collecting exhaust air below slat level and returning into building to connect with main outlet ducts.

Figure 5. Inside view of the laboratory showing the location of the upper exhaust duct.

the ducts. Efficient use of the materials used in the fabrication of the ducts also was considered, that is, obtaining the maximum amount of material out of standard 4 feet by 8 feet sheets of masonite. According to Jorgenson (35), the velocity of the air flowing over a wet-bulb thermometer must be between 500 and 1000 feet per minute to ensure that its temperature is equal to that of adiabatic saturation of air with water vapour. As a result, the exhaust ducts were 16 inches by 16 inches and the common ducts were 16 by 24 inches. The outlet ducts were 24 inches by 32 inches. A ten foot stack with the dimensions of the outlet duct was placed on the end of each outlet duct as shown in figure 6 to minimize the risk of recirculation of the exhausted air. In the upper and lower exhaust ducts,the air velocity was 840 feet per minute and 1100 feet per minute for the 3000 and 4000 cubic feet per minute ventilation rates respectively. The air velocities of the outlets were 560 and 750 feet per minute for 3000 and 4000 cubic feet per minute ventilation rates respectively,while the inlet duct velocities were 1000 and 1333 feet per minute respectively down stream from the fan where the moisture content and gas concentrations of the incoming fresh air were measured.

To accommodate low level exhausting in the straw-bedded housing system, a 2 feet high false wall of 3/5 inch plywood was constructed 3 1/2 inches out from each external wall. This allowed the air to pass freely to the exhaust slots immediately below floor level. All the air had to pass through these openings as these were the only means by which air could reach the pits beneath the floor since the gaps between the floor and the trough was enclosed.

4.1.4 Rotors.

The rotors or rotary agitators used in this project had been

designed and used in an earlier experiment conducted in this same laboratory on the effects of aeration on the composition of beef cattle wastes. In his project, Aasen (1) noted that use of the rotors appeared to increase the rate of evaporation from the storage pits. For this reason, the rotors were added as a further parameter for study in this project to determine their effects on moisture removal rates. Their use also provided an opportunity to investigate the effects of the resultant aerobic pit conditions on noxious gas removal rates compared with those under anaerobic pit conditions.

The rotors were located in two of the pits beneath the slatted-floor housing system. One rotor assembly was situated in the first pit while two rotor assemblies were located in the second (figure 3). It must be noted that these two pits each have a 6 inch thick center dividing wall 6.5 feet high, extending to within 4 feet from each end of the pit. The corners of these pits were rounded with metal sheeting to form an 'oval track' oxidation ditch.

Each rotor assembly consisted basically of a motor, reduction gear, and a rotor. The motor and reduction gear were located under the feed bunk, with removable floor panels in the feed bunk for inspection and maintainance. The concrete slats could also be removed to service the rotor assemblies. Each rotor was 30 inches in length with a diameter of 32 inches and operated at 120 revolutions per minute (figure 7). The rotor blades or teeth were made from one inch angle iron and were 14 inches in length. The teeth were welded to a hollow 4 inch outside diameter metal pipe in eight staggered rows of seven and eight teeth per row spaced 45° apart. This metal pipe enclosed a longer stainless steel shaft upon which a sprocket was mounted.

Figure 6. South end of the laboratory showing position of the exhaust stack (to the right) used to minimize recirculation into the hooded inlet (to the left).

Figure 7. A rotor assembly in lowered position beneath the slatted floor.

The bearings used were hardwood which proved very satisfactory. The rotor assembly pivoted by means of a shaft fastened to the slats by 2 pillow blocks. The reduction gear drove the pivot shaft which, in turn, drove the rotor shaft via stainless steel chains. In this way, the depth of operation of the rotor in the slurry could be adjusted to maintain an average constant value of three inches. A hand winch and cable to each rotor assembly were used to make the necessary depth adjustments. A full description of the rotor design has been detailed by Aasen (1).

Rotor maintanance was minimal with the two assemblies in operation in the second pit. Breakdowns of the single rotor were more frequent due to the added load. If a breakdown did occur, it was serviced within four to five hours to ensure that the experiment was not adversely affected. Some of the common failures were in the bearings and shafts due to the high rate of corrosion. Each rotor was submersed two to four inches in slurry to provide the necessary aeration action. Aasen (2) found that the slurry had to be circulated at an approximate rate of 20 feet per minute to ensure good aeration and suspension of solids. Failure in doing this led to foaming. The depth of slurry in these pits varied between one and four feet during the course of the experiment. When the two assemblies were operating in the second pit the depth of the slurry was quite stable because of the increased evaporation.

4.2 Instrumentation

4.2.1 Temperature Instrumentation.

Copper-constantan thermocouples were used for temperature measurements. In all, thirty thermocouples were used within the building. As shown in figures 2 and 8, two thermocouples were placed in each of the outlet ducts and two were located in each of the lower and upper exhaust ducts. Two thermocouples also were situated down-stream and one up-stream

from each fan in the two inlet ducts. The remaining two thermocouples were each used to measure ambient temperature in the two housing systems. The thermocouple up-stream from the fan measured the outside air temperature.

These thermocouples were wired into a Honeywell 24-point temperature recorder located in the center of the building. The recorder was equipped with a switching device to permit sequential recording from the thermocouples located in either the low level ducts or from those located in the upper level ducts, depending on which of the two exhaust levels was in operation. The thermocouples from the outlets, the inlets and the two environmental chambers bypassed the switching device and were wired directly into the recorder. The temperatures were recorded 20 minutes in each hour, the operation of which was controlled by a time clock. Temperature data was obtained from the recorder every two hours since it was observed that little fluctuation in temperatures occurred over a several hour period. These temperatures were read to the nearest degree since the vapour pressures used applied only to whole degrees of temperature (35).

As previously mentioned, the thermocouples were located in pairs in the exhaust and inlet ducts. One of these thermocouples measured the dry-bulb temperature while the other measured the wet-bulb temperature of the air. Each wet-bulb thermocouple lead was covered with a wet wick the other end of which was inserted into a water bath. The wet-bulb wicks in the exhaust ducts had to be serviced daily because of the prevailing dusty conditions. Preliminary investigations indicated that the wet-bulb temperature error was relatively small if they were cleaned daily. In the inlet ducts, the wet-bulb

thermocouples required servicing only every ten days because of the clean air entering the building during the winter period. When the wicks were beyond cleaning, they were replaced.

The accuracy of the wet-bulb thermocouple seemed to vary directly with the temperature differential between the dry and the wet-bulb thermocouples as checked by a sling psychrometer. In the inlet ducts, a high temperature differential existed since the air was heated and contained a small amount of moisture. To minimize the heat from the surrounding air from being conducted along the thermocouple lead to the junction, the lead was covered with four inches of wick. According to Beckwith and Buck (8), the potential resulting from a temperature gradient along the thermocouple lead, known as the Thompson electrical potential, is quite small relative to the Peltier electrical potential, which is the potential resulting from the contact of two dissimilar metals and the junction temperature. The wet-bulb thermocouple leads in the exhaust ducts were covered with one inch of wick since a small temperature differential existed in this case. In comparison with the wet-bulb readings of the sling psychrometer, the error of the wet-bulbs in the exhaust ducts was $\pm 0.5^{\circ}F$ while the error of the wet-bulbs in the inlet ducts was $\pm 1.0^{\circ}F$. Periodically, each thermocouple was calibrated using an ice bath as the standard reference. The mean deviation of the thermocouple temperatures recorded was $\pm 0.5^{\circ}F$.

4.2.2 Gas Analyzers

Measurements of the CO_2 and NH_3 gas concentrations were made using two Beckman Model 315A non-dispersive infrared analyzers. One instrument was specifically for CO_2 while the other was specifically for NH_3. The analysis is based on a differential measurement of the

absorption of infrared energy. Two infrared sources are used, one for the sample energy beam, the other for the reference energy beam. The beams are blocked simultaneously 20 times per second by a chopper, which is a segmentated blade rotating at 5 revolutions per second. While the beam is unblocked, it passes through its respective cell and into the detector (7).

The sample cell is a flow-through tube while the reference cell is a sealed tube filled with a reference gas. This reference gas is selected for minimal absorption of infrared energy of those wavelengths absorbed by the sample component of interest. The detector consists of two compartments separated by a flexible metal diaphragm. The difference in energy entering the detector distends the diaphragm when the beam is unblocked. When the beam is blocked, the temperature and pressure equalizes in the compartments and the diaphragm retains its original position. Thus, as the beams are blocked and unblocked, a pulse occurs which is converted electronically to a per cent deflection on a voltmeter scale. The gas concentration of the associated sample is determined by a calibration curve. The CO_2 and NH_3 data were recorded on a Sanborn two-channel hot wire recorder, the operation of which was controlled by means of a time clock set to provide 5 minutes recording in each hour (figure 9).

The ammonia analyzer proved very sensitive to fluctuations in temperature within the instrument room. A heater with a thermostat alleviated the problem appreciably, but did not entirely eliminate it.

4.2.3 Manometer

The ventilation rate within the building was determined by

Figure 8. Gas probes and filter, dry and wet-bulb thermocouples with the associated wick and reservoir.

Figure 9. Gas analyzers, pump and two-channel recorder in the instrument room.

measuring the velocity pressures within the inlet duct down-stream from the fan. The manometer was connected to a pitot static tube. The manometer fluid was of a specific gravity of 0.826. The accuracy of the unit was rated as ±150 cfm.

4.2.4 Feed Scale

All the feed that was fed to the animals within the Environmental Laboratory was weighed directly in the feed-cart, the cart being suspended from a section of the monorail which was an integral part of a weigh scale set-up. Moisture determinations of the haylage were carried out on samples taken during each feeding. The grain and protein supplement ration moisture determination was carried out twice during the experiment since the moisture level of this feed had been previously found to be consistent at a moisture content of 13.5 per cent.

4.2.5 Cattle Scale

The cattle were weighed on a scale using strain gauges as a means of measurement. They were weighed at 28 day intervals during the duration of the experiment. The cattle weights were correlated with gas and moisture removal.

4.2.6 Manure Samplers

4.2.6.1 Straw-bedding manure sampler.

Sampling of the manure pack was done by means of a core sampler mounted on a 0.5 inch drill. The diameter of the core sampler was 3.5 inches and the length was approximately one foot. It consisted of a 3.5 inch cylinder with a top fastened to it which, in turn connected to the drill by means of a 0.5 inch rod. The end of the cylinder was sharpened, thus serving as a cutting edge for the straw

and manure (figure 10).

4.2.6.2 Liquid manure sampler.

This was used to collect a sample of liquid manure from the pits beneath the slatted floor for moisture determination. It consisted of a 12 feet rod within a 12 feet pipe. The end of the rod was connected to a plunger. By lowering the sampler into the manure and then pulling the rod so that the plunger was seated against the pipe, the slurry sample was trapped within the pipe. A moisture determination of the liquid manure was obtained every ten days since the percentage moisture did not increase substantially, as found by Aasen (2).

4.2.7 Water Meters

Three water meters were used to measure the water consumed by the animals (figure 11). Two of these meters were situated in the straw-bedded housing system while the third was connected into the main line. The two meters in the straw-bedded area were calibrated to read in gallons while the other on the main line measured flow in cubic feet. By subtracting the total of the water consumed by the animals in the straw-bedded housing system from the total consumption, the consumption was determined for the animals in the slatted-floor housing system.

4.3 Methods

4.3.1 Moisture Determination in the Manure Pack

The three pens in the straw-bedded housing system were each divided into a grid of nine equal rectangles. The depth measurements were taken in the center of each of these rectangles (figure 12). The average depths were calculated for each pen. The manure samples were

Figure 10. The gas sampling filter, measuring probe and manure sampler used in determining the moisture content of the manure pack.

Figure 11. Interior view of the straw-bedded housing system showing the upper exhaust duct and water meter.

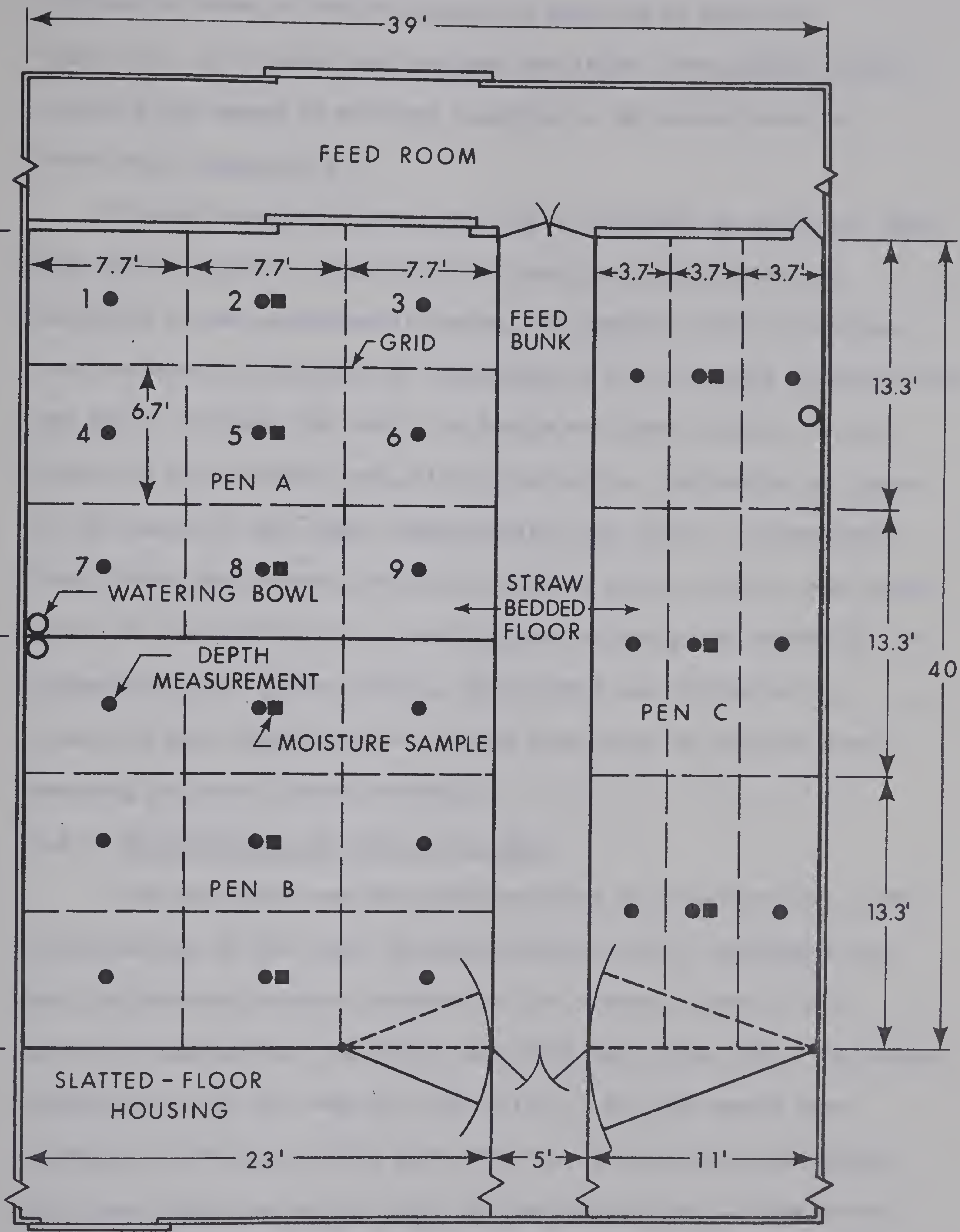


Figure 12. Grid arrangement in the straw-bedded area for depth measurement and moisture content sampling.

obtained in three of the rectangles in each pen as shown in figure 12. The samples were weighed and dried. The method of calculating the amount of moisture existing in the manure pack is described in Appendix 2.

To avoid sampling in the same place, a system was used such that this did not occur. Since two trial runs occurred together as described in the experimental design, the samples prior to the runs were obtained to the south of the center of the rectangle (approximately one foot). Between the runs, the sample was taken exactly at the center of the rectangle and, after this period, the sample was taken to the north of this point (approximately one foot). It was found that, after this period, the first sampling point could be used again since all the evidence of a sampling hole existing was removed by the trampling action of the cattle. This method was considered to result in more representative samples than could be obtained from sampling at points chosen randomly.

4.3.2 Determination of Ventilation Rate

The procedure used was that described by Jorgenson (35). The cross-section of the inlet duct was divided into 25 rectangles and and the velocity pressure measured at the center of each. This procedure was carried out before and after each trial run. The average ventilation rate was used for that period. The fan speeds were adjusted to 800 rpm so that both fans each delivered approximately 3000 cubic feet per minute. The fan capacity varied to some extent depending on outside wind velocity and direction. The bird screens on the inlet ducts also caused some variation in fan capacity by frosting up occasionally if a high humidity existed in the outside

air, thus increasing resistance to air flow. The method of calculating the ventilation rate from the velocity pressures recorded is described in Appendix 1.

4.3.3 Start-Up Procedure

Before and after each trial run, a series of measurements were undertaken in order to establish a moisture balance within each of the two housing systems. Each trial run was started at the same time of the day during the experiment. The first gas and temperature data recording took place an hour after each trial run commenced. Prior to and after each trial run, manure samples of the straw bed were taken and the depth of the manure pack at 27 different points were measured. The depth of slurry in the pits under the manure pack and the slatted floor were measured prior and subsequent to each trial run to the nearest 1/8 inch. The water readings also were taken before and after each trial run. Before each trial run, the wicks on the wet-bulb thermocouples were changed or cleaned because of the debris which tended to lodge on them.

The amount of feed fed to the animals during each trial run was recorded so that the amount of moisture entering the building via the feed could be determined. Straw used for bedding introduced a minimal amount of moisture and, therefore, was not considered in the moisture balance.

Brannigan (13) stated that, under normal conditions in livestock buildings, a dynamic equilibrium exists between the rate of gas production and the rate of gas exhausted in the ventilating air. In practice, one hour was considered sufficient to provide a CO_2 and an NH_3 equilibrium within the building. With regard to moisture

equilibrium, one hour also was considered sufficient to obtain stable absolute humidities of the exhausted air following any change in the exhaust levels.

4.3.4 Gas Sampling Procedure

The CO_2 and NH_3 concentrations were measured in the same location as the wet and dry-bulb thermocouples in the main exhaust duct for each housing system. Three 1/4 inch outside diameter copper pipes were used to extract the air from each exhaust duct. These pipes were placed horizontally in the duct so that the air was extracted at one third, one half, and two thirds the width of the duct. These probes were evenly spaced in a vertical arrangement along the side of the duct (figure 8). All three copper pipes had a common filter consisting of three layers of very fine silk. These were serviced once a week.

Plastic tubing of 1/4 inch diameter was used to interconnect the copper pipes, filter, valve, and the main plastic line which ran the distance of the building into the gas analyzers located in the instrument room within the feed room. A sampling pump was used to draw the air from the ducts to the gas analyzers. Only one copper pipe was inserted into the inlet duct of each housing system since the air was considered to be adequately mixed down-stream from the fan.

During each trial run, two samples were obtained from each operating exhaust duct and the inlet duct in the housing system in which the gases were monitored. It should be noted that the monitoring of the gases could be undertaken only within one housing system at a time. The CO_2 which entered the housing systems was obtained from a calibration curve presented in Appendix 5. This curve was based on the temperature differential between the outside and the incoming air down-stream from

the furnace. The CO_2 input to the housing systems was found to vary directly as this temperature differential since a linear relationship existed between the heat and the CO_2 produced by the furnace. This relationship was established and checked several times before the experiment.

The NH_3 concentration of the incoming air was checked twice during each trial run. The concentrations were found to be relatively constant. Towards the end of the experiment, the NH_3 concentrations in the incoming air increased, the reason most probably being due to increasing quantities of NH_3 being released from adjoining feedlots by volatization as spring temperatures increased.

The air also was monitored at animal level twice during each trial run. The time required to monitor at animal level was such that a representative sample could be obtained from the housing system being monitored. For the purpose of analysis, the mean concentrations were compared with the mean concentration exhausted from the housing system at that particular time. The concentrations of the individual exhaust ducts were also compared with the concentration of the main exhaust duct.

The remainder of each trial run was allocated to sampling the exhaust air at the outlet. These concentrations were recorded on the two-channel, hot wire recorder five minutes of every hour, the recorder operation being controlled by a time clock. The time clocks controlling the operation of the temperature recorder and that of the gas analyzer recorder were synchronized so that the temperature and gas data were obtained at the same time although for different durations. It must

be noted that the temperature data were obtained every two hours but was recorded every hour. The details of how the gas sampling was alternated from one housing system to another is described in the experimental design and Appendix 7.

4.3.5 Experimental Design

The experiment was divided into three parts in which three individual phases were involved, with regard to the water vapour removal rate, the NH_3 and the CO_2 removal rates from each treatment considered. The first part of the experiment dealt with the influence of different ventilation and housing systems on moisture and noxious gas removal. The second part of the experiment involved the effect of the rotors and ventilation systems on moisture and noxious gas removal in the slatted-floor housing system. The effect of increased ventilation and ventilation systems or exhaust levels in the straw-bedded housing system was studied during the third part of the experiment. The ventilation rate was increased from approximately 3000 to 3700 cubic feet per minute. It should be noted that, in the first two parts of the experiment, the ventilation rate was approximately 3000 cubic feet per minute.

The duration of each trial run was 48 hours, in which the temperatures and gas concentrations were recorded every hour. Before and after each trial run, the necessary measurements also were carried out for the purpose of establishing a moisture balance as described in the experimental procedure. In the first part of the experiment, the water vapour removal rates and the moisture balance were determined simultaneously in both housing systems. Thus, each trial run consisted of either lower or upper exhausting of the room air. In this part of the experiment, three rotors were in continuous operation in the slatted-

floor housing.

The second and third parts of the experiment were carried out simultaneously, that is, the second part of the experiment occurred in the slatted-floor housing system while the third occurred at the same time in the straw-bedded housing system. For the second part of the experiment, the effect of the rotors on moisture and noxious gas removal was studied. The treatments consisted of two, one, and no rotors in operation. For each treatment, the trial runs consisted of either lower or upper exhausting. Ammonia and CO_2 were monitored continuously throughout this part of the experiment.

During the third part of the experiment, which dealt with an increased ventilation rate, the NH_3 and CO_2 concentrations were not recorded since gas concentrations could only be monitored in one housing system. With respect to the moisture balance, the water content of the straw bed was not determined by sampling. Instead, it was calculated as the water present in the straw bed was the only unknown parameter in the moisture balance, that is, all other moisture parameters were known.

Effectiveness of removal or removal rate was the parameter in each study upon which the statistical analysis was based. The water vapour removal rate was the difference between the water vapour exhausted and the water vapour present in the incoming ventilation air in lb per hour. The NH_3 and CO_2 removed by the ventilation air was also determined by simply subtracting the incoming from the exhaust concentrations. These differences were determined every hour during the trial run. For the purposes of analysis, the hourly removal rates were averaged for each trial run. Since the treatments considered were not studied at

the same time interval within the course of the experiment and since the ventilation rates differed for each ventilation and housing system, a common denominator to express the effectiveness of removal for both the water vapour and the gases was considered necessary. As a result, the water vapour and the gas removal rates were expressed in terms of units of exchange air and units of animal weight. For the water vapour (WVRR) and the CO_2, the units were in terms of 1000 cubic feet per minute of air and 10,000 pounds of liveweight, respectively. For NH_3, the units were expressed in terms of 10,000 cubic feet per minute of air and 10,000 pounds of liveweight, respectively, since these concentrations were very low.

The three studies were of a split plot design with a 2 x 2 latin square within the whole plots. A 2 x 2 latin square was selected as a subplot since only one sub-treatment was used, namely the two exhaust levels. The top row within the latin square consisted of the upper exhaust level trial run followed immediately by the lower exhaust level trail run or vice versa. After this period of time, one day was allotted to serve as a break period, with the next two consecutive trial runs starting but in opposite order from the first set of trial runs. These two sets of trial runs were considered as one block. In the following block or latin square, the second row of the former block became the first row while the first row of the former block became the second row of the second block. These two blocks constituted a replicate. This arrangement ensured that each type of trial run was followed by another an equal number of times. The effect of the time break between the two consecutive and the trial runs following each other also was studied.

This type of experimental design required two other parameters to be inserted within the split-plot, namely the sequence of trial runs and periods. The first set of runs within each block were denoted by period 1 while the second set of runs within each block were denoted by period 2. The term 'sequence' refers to the order of trial runs within each period (table 1).

TABLE 1. ARRANGEMENT OF THE EXPERIMENTAL TRIAL RUNS.

Block 1	Period 1	Sequence 1	L - U-break period*
	Period 2	Sequence 2	U - L-break period
Block 2	Period 1	Sequence 2	U - L-break period
	Period 2	Sequence 1	L - U-break period

* L - lower exhaust level
U - upper exhaust level

The first part of the experiment consisted of three replicates in which the gases were monitored during the first and third replicate in the straw-bedded housing system and in the slatted-floor housing system during the second replicate. In the second part of the experiment, three replicates were also considered except that each replicate consisted of one treatment, namely, two operating rotors, one operating rotor, and no rotors in operation. The gases were monitored for these three replicates. For the purposes of comparing the rotors, the mean water vapour removal rate from the three operating rotors was used. The third experiment also consisted of three replicates. It should be noted that the gases could only be monitored in one housing system at one time.

5. DATA ANALYSIS AND RESULTS

5.1 Methods of Data Analysis.

The statistical procedures used in analysing the data obtained involved the analysis of variance and multiple regression analysis.

5.1.1 Independent Variables

The sources of variation, their levels and codes used in the analysis are shown in table 2.

TABLE 2. LIST OF VARIABLES, CODES AND LEVELS.

Variable	Code	Levels
LEVEL	L	L1 - upper exhaust level (6.5 feet above floor) L2 - lower exhaust level (0.5 foot below floor)
HOUSING	H	H1 - straw-bedded housing system H2 - slatted-floor housing system
ROTORS	R	R0 - no operating rotors R1 - one operating rotor R2 - two operating rotors R3 - three operating rotors
VENTILATION RATE	V	V1 - 2968 cfm (mean value) V2 - 3727 cfm (mean value)

5.1.2 Analysis of Variance

The analysis of variance of the data in Appendices 8 and 9 was carried out on the basis of a latin square existing within a split-plot design. The different factors considered were housing systems, ventilation rates and rotors. These treatments occupied the main plots while the two exhaust levels occupied the subplots. The analysis of variance techniques determined if the differences occurring in the moisture, carbon dioxide and ammonia removal rates for the treatments

were significantly different. These calculations were performed using the University of Alberta Computing Centre library program (19). If the treatments considered were significantly different and if more than two means were compared, then Duncan's New Multiple Range Test (51) also was applied in order to determine which of the treatments compared were significantly different.

5.1.3 Multiple Regression

A multiple regression technique was used to determine how much of the variation in the moisture, carbon dioxide and ammonia removal rates occuring within each housing system could be explained by the following variables: total weight of the animals for each treatment, water consumption of the animals and the number of operating rotors. This technique was used for each exhaust level in its respective housing system. Prediction equations were calculated based on the data obtained.

5.2 EXPERIMENT 1 - WATER VAPOUR REMOVAL RATE

5.2.1 Housing Systems

The mean values which appear in table 3 are presented in figure 13 to illustrate the trends. This graph illustrates the water vapour removal rate (WVRR) for each of the exhaust levels within their respective housing system. Three rotors operated in the slatted floor system during this treatment. It should be noted that the water vapour removed per hour (WVR/hr) is expressed in terms of 10,000 lbs of animal weight and in terms of 1000 cubic feet per minute (cfm).

TABLE 3. WATER VAPOUR REMOVAL RATES FOR TWO HOUSING SYSTEMS.

Treatment	WVR/hr/cfm/lb x 10^{-7}
H1	7.56
H2	7.89
L1	7.31
L2	8.13
H1 x L1	7.40
H1 x L2	7.72
H2 x L1	7.22
H2 x L2	8.55

5.2.1.1 <u>Analysis of Variance Results for the Water Vapour Removal Rate</u>

The analysis of variance for the WVRR within the housing systems are shown in table 4. The calculated F values in the analysis of variance indicated that the overall differences due to housing systems were not significant. The differences due to the exhaust levels were highly significant ($P<0.01$). The interaction between housing and exhaust levels was of greatest interest. This was significant at the 5 per cent level of probability. Figure 13 shows that the WVRR was higher for the slatted-floor housing system than for the straw-bedded housing system while a higher WVRR occurred for the lower exhaust level in both housing systems. The significant differences occuring within the blocks could be attributed to error.

TABLE 4. ANALYSIS OF VARIANCE - WATER VAPOUR REMOVAL RATE

Source of Variation	Degrees of Freedom	Mean Squares	F
H (Housing)	1	1.3	< 1
B (Blocks)	5	21.9	7.19*
Error (1)	5	3.1	
L (Level of exhaust)	1	8.1	13.67**
P (Period)	1	2.1	3.58
S (Sequence)	1	1.5	2.45
LH	1	3.1	5.28*
PH	1	3.4	5.74*
SH	1	0.0	< 1
Error (2)	30	0.6	
	47		

* Significant at the 0.05 level of probability.

** Significant at the 0.01 level of probability.

5.2.2 Ventilation Rates

Two different ventilation rates were introduced in the straw-bedded housing systems during the course of the experiment. The mean WVRR values obtained are given in table 5 and are displayed in figure 14 to show the trends.

The graph (figure 14) shows the effect of ventilation rates and exhaust levels on WVRR. The overall mean WVRR for the lower ventilation rate was higher than the overall mean WVRR for the higher ventilation

TABLE 5. WATER VAPOUR REMOVAL RATES FOR THE TWO VENTILATION RATES

Treatment	WVR/hr/cfm/lb x 10^{-7}	WVR/hr/lb x 10^{-4}
H1V1	7.56	22.50
H1V2	5.51	20.60
L1	6.42	
L2	6.66	
V1 x L1	7.40	
V1 x L2	7.72	
V2 x L1	5.43	
V2 x L2	5.59	

rate. The two rates were in the ratio of 1.27:1.00. The WVRR for the two exhaust levels followed the same trend as the WVRR for the two housing systems in that the WVRR was lower for the upper exhaust level. The overall mean WVR/hr for the lower ventilation rate was also higher than the overall mean WVR/hr for the higher ventilation rate when expressed only in terms of liveweight.

5.2.2.1 Analysis of Variance for Water Vapour Removal Rate

The analysis of variance for the WVRR is shown in table 6. In this case, the main effect ventilation rate is highly significant while no significant differences occurred between the exhaust levels. The interaction between ventilation rates and exhaust levels was not significant. However, for the purpose of discussion, the interaction

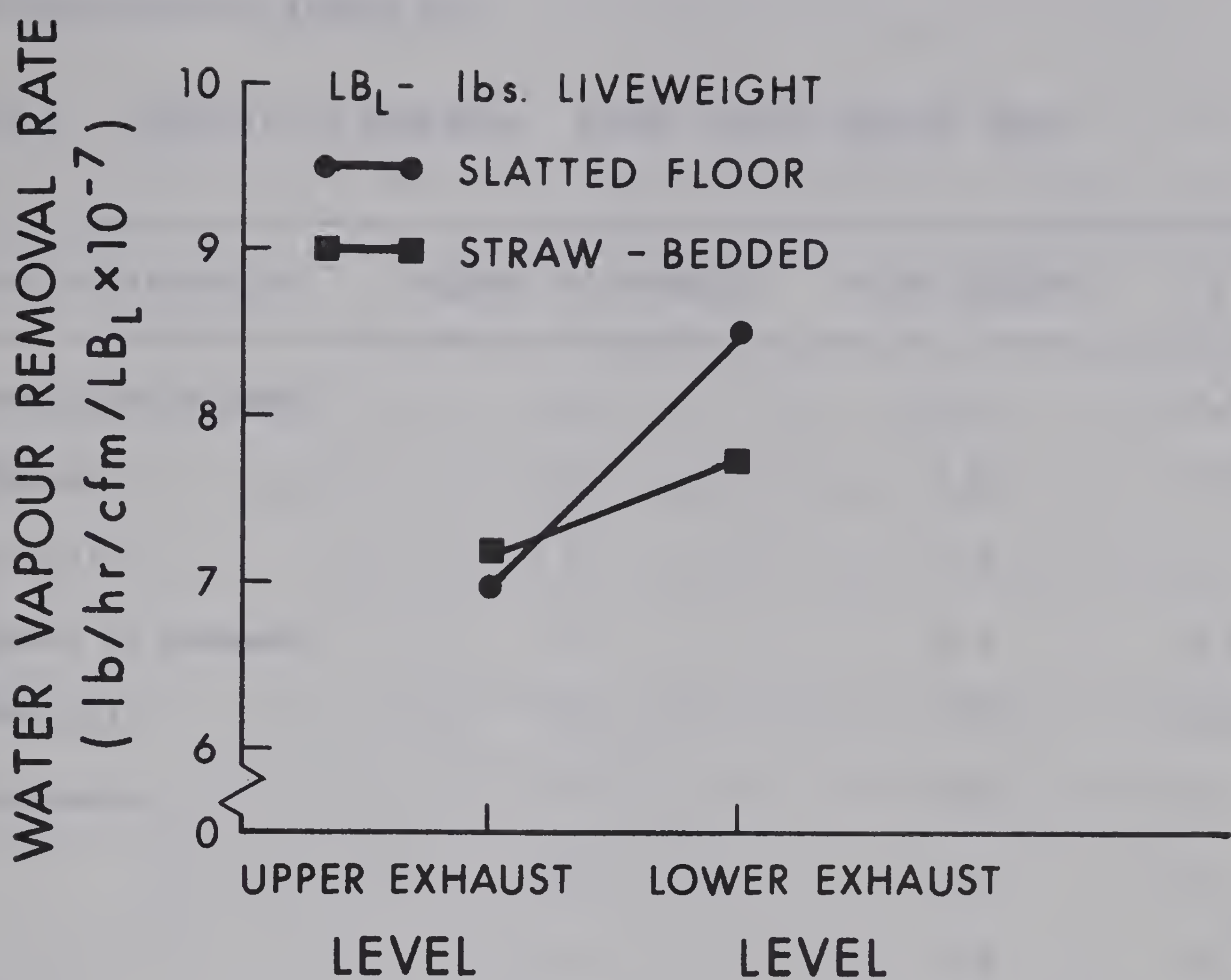


Figure 13. Graph illustrating the effect of housing systems and exhaust levels on the water vapour removal rate.

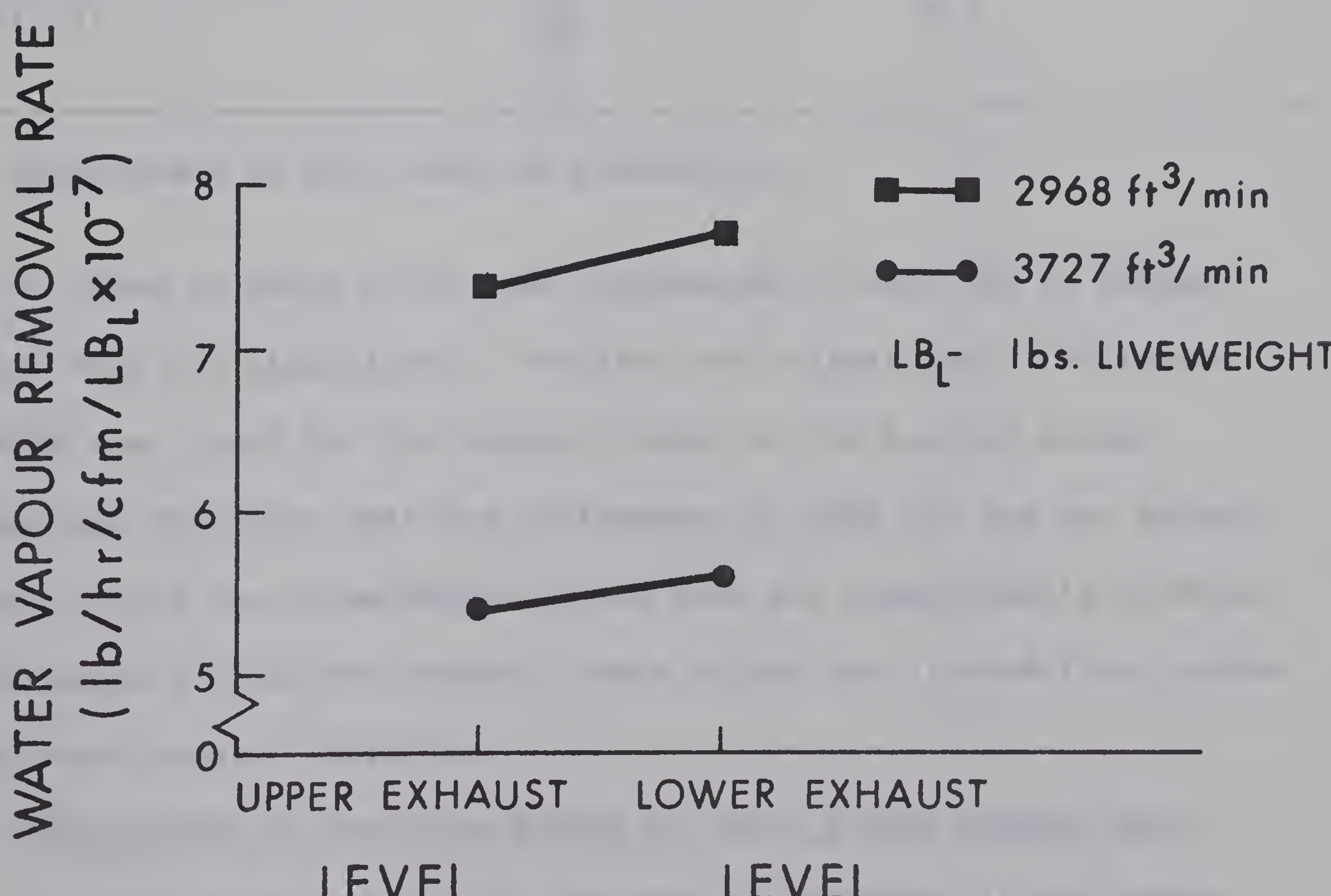


Figure 14. Graph illustrating the effect of ventilation rates and exhaust levels on the water vapour removal rate in the straw-bedded housing system.

is illustrated in figure 14.

TABLE 6. ANALYSIS OF VARIANCE WATER VAPOUR REMOVAL RATE

Source of Variation	Degrees of Freedom	Mean Squares	F
V (Ventilation Rate)	1	50.4	29.57**
B (Block)	5	9.0	5.30
Error (1)	5	1.7	
L (Level of exhaust)	1	0.7	1.91
P (Period)	1	0.7	1.26
S (Sequence)	1	0.1	<1
LV	1	0.1	<1
PV	1	1.4	2.78
SV	1	2.1	4.06
Error (2)	30	0.5	
	47		

** Significant at 0.01 level of probability.

As shown in table 6, the mean differences in WVRR due to exhaust levels were not significant. The fact that significant differences in WVRR were found for the exhaust levels in the housing system comparison indicates that the differences in WVRR for the two exhaust levels within the straw-bedded system were not significantly different while those for the two exhaust levels within the slatted-floor system were significantly different.

5.2.3 The Effect of Operating Rotors on Water Vapour Removal Rate

In this study, an attempt was made to determine if the number

of operating rotors resulted in a significant change in the WVRR. The WVRR values found for the different number of rotors operating in the slatted-floor system also were compared with the WVRR values found for the two ventilation rates within the straw-bedded system. The mean values of the different treatments with their interactions are listed in table 7 and are plotted in figure 15. The graph illustrates the effect of the rotors and the comparison of the housing systems. The effect of the exhaust levels is also plotted.

TABLE 7. MEAN WATER VAPOUR REMOVAL RATES FOR THE OPERATING ROTORS IN THE SLATTED-FLOOR SYSTEM, AND STRAW-BEDDED HOUSING SYSTEM WITH THEIR INTERACTIONS.

Treatment	WVR/hr/cfm/lb x 10^{-7}
L1	6.35
L2	6.99
R3	7.89
R2	6.97
R1	5.03
R0	5.21
H1V1	7.56
H1V2	5.51
L1 x R3	7.22
L2 x R3	8.55
L1 x R2	6.28
L2 x R2	7.66
L1 x R1	4.47
L2 x R1	5.60
L1 x R0	5.34
L2 x R0	5.08
L1 x V1H1	7.40
L2 x V2H1	7.72
L1 x V2H1	5.43
L2 x V2H1	5.59

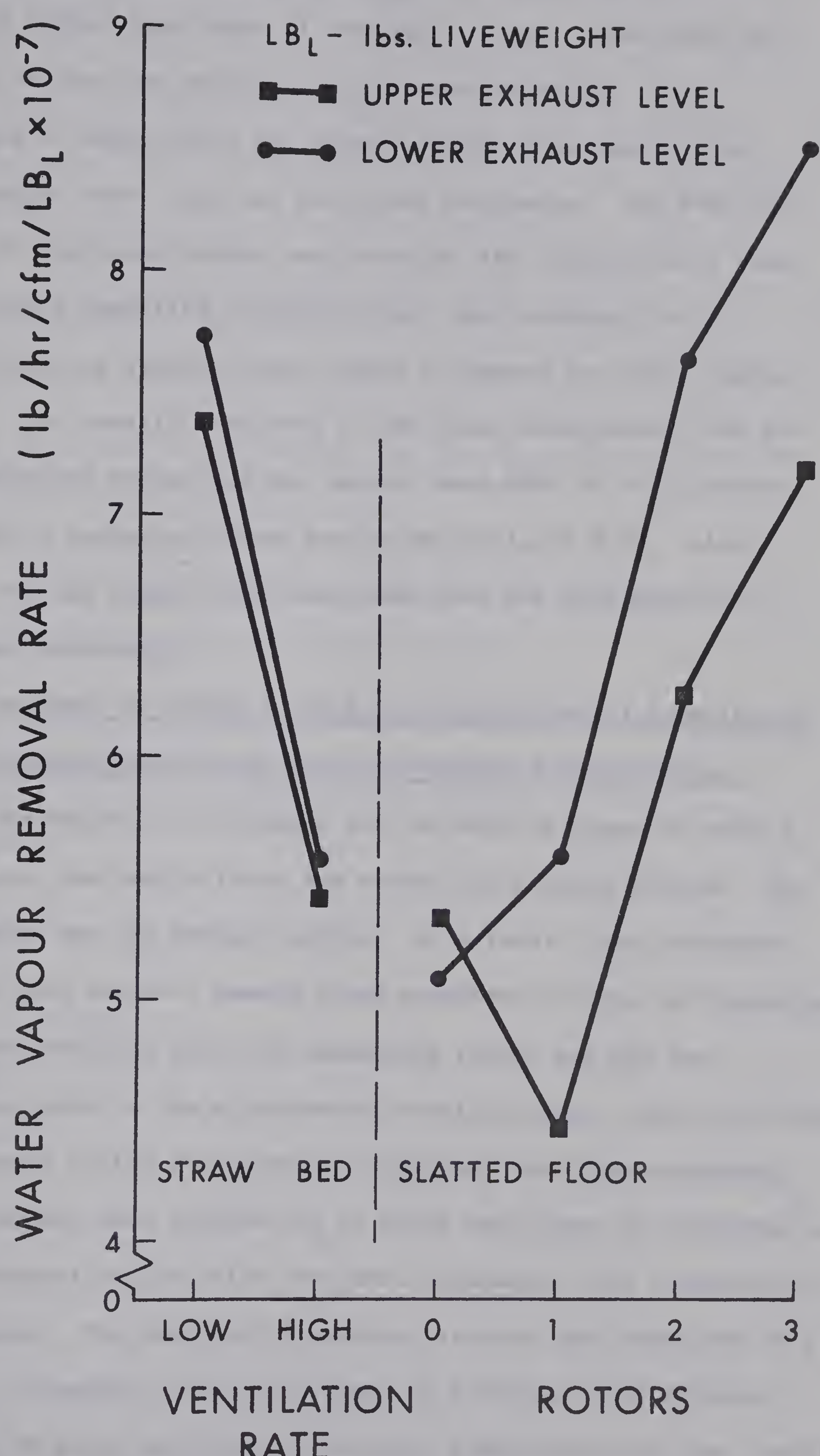


Figure 15. Graph illustrating the effect of the rotors in the slatted-floor housing system and the straw-bedded housing system on the water vapour removal rate at the two exhaust levels.

As shown in figure 15 the WVRR values at the lower exhaust level were higher than those of the upper exhaust level with the exception of the case where no rotors were operating. The differences in WVRR within the exhaust levels were greater for the operating rotors than for the other treatments. The WVRR was greater for the straw-bedded area than for the slatted-floor area with no rotors operating indicating that less exchange air is required with the slatted-floor system to remove the water vapour produced. The overall mean WVRR of the lower ventilation rate for the straw-bedded system and the overall mean WVRR of the slatted-floor with no operating rotors was in the ratio of 0.82. Also, the WVRR for the single rotor was lower than the WVRR when no rotors were operating.

5.2.3.1 Analysis of Variance for Water Vapour Removal Rate for the Operating Rotors and the Straw-Bedded Housing System.

The analysis of variance for the WVRR is shown in table 8. In this case, the main effects are rotors and housing systems. The subtreatments are the exhaust levels. As a result, six treatments were taken into account, namely three operating rotors, two operating rotors, one operating rotor, no operating rotors and the two ventilation rates in the straw-bedded housing system. Each ventilation rate treatment in the straw-bedded system and the three operating rotors treatment were carried out in three replicates as described in the experimental design while the other treatments each consisted of one replicate. The analysis of variance treated each replicate as a treatment. Therefore, for the purpose of plotting the treatments consisting of three replicates, they were simplified such that overall means from each of the three replicates were obtained from tables 3 and 5.

The differences in the overall means of the treatments considered were significant at the 0.05 probability level. The exhaust levels also demonstrated highly significant differences as was the case in the housing system comparison. The interaction treatment and exhaust level was highly significant as shown in figure 15. Period was also highly significant indicating that there was an effect of the second set of runs being followed by the first set of runs within each block. In this case, the means of the first set was significantly higher than the mean of the second set of consecutive runs within each block.

TABLE 8. ANALYSIS OF VARIANCE FOR WATER VAPOUR REMOVAL RATE WITH CHANGING NUMBER OF OPERATING ROTORS.

Source of Variation	Degrees of Freedom	Mean Square	F
T (Treatment)	11	18.1	3.01*
B (Block)	1	6.3	1.05
Error (1)	11	6.0	
L (Level of exhaust)	1	9.9	35.73**
P (Period)	1	4.8	17.26**
S (Sequence)	1	0.2	<1
LT	11	1.0	3.65**
PT	11	0.8	2.81**
ST	11	1.0	3.51**
Error (2)	36	0.3	

* Significant at the 0.05 level of significance
** Significant at the 0.01 level of significance.

5.2.3.2 Duncan's New Multiple Range Test

A Duncan's new multiple range test was carried out to determine which of the treatment means were significantly different since the F test in the analysis of variance indicated only that significant differences between treatment means existed (51). The treatment means with their respective superscript are presented in table 9. Treatments not followed by the same superscript are significantly different from each other at the 5 per cent level as judged by Duncan's multiple range test.

TABLE 9. SIGNIFICANCE AMONG THE TREATMENT MEANS

H1V1 (REP1)	8.93a	R3 (REP1)	9.56a
H1V1 (REP2)	6.46c	R3 (REP2)	6.89bc
H1V1 (REP3)	7.29b	R3 (REP3)	7.21b
H1V2 (REP1)	6.58c	R2	6.97bc
H1V2 (REP2)	4.86d	R1	5.03d
H1V2 (REP3)	5.09d	R0	5.21d

The three treatments with the three replicates were inconsistent in that significant differences occurred within each treatment suggesting that the data contained appreciable error or that these differences were due to other parameters. One and no operating rotor were significantly different from the two operating rotors, three operating rotors, and the ventilation rate of 2968 cfm in the straw-bedded housing system. The treatments consisting of two or three operating rotors within a slatted-floor housing system and the lower ventilation rate

within the straw-bedded system were comparable in that the overall mean WVRR values were not significantly different.

The wet and dry-bulb temperatures from the side ducts were not analyzed but were available. In order to compare the WVRR values from each exhaust duct the mean air flow had to be determined for each trial run. This was not done. These thermocouples were set up to serve as a means of checking the thermocouples in the main exhaust.

5.3 EXPERIMENT 2 - AMMONIA

In this experiment, five treatments were considered; namely, three operating rotors, two operating rotors, one operating rotor and no rotors operating in the slatted-floor system and the two replicates of the straw-bedded housing system. The overall means of efficiency of NH_3 removal for each treatment are presented in table 10 and plotted in figure 16. It should be noted that this efficiency is expressed in terms of 10,000 cfm and 10,000 lb animal liveweight.

In each treatment considered, the lower exhaust level removed more ammonia than the upper exhaust level. The overall difference of the five treatments was six ppm/10,000 cfm/10,000 lb liveweight which is very small in a practical sense.

TABLE 10. MEAN EFFICIENCIES FOR AMMONIA REMOVAL

Replicate	Treatment	NH_3 ppm/cfm/lb x 10^{-8}
1	H1VI	12
2	H1V1	12
	R3	14
	R2	18
	R1	18
	R0	13
	L1	12
	L2	17
1	H1V1 x L1	10
	H1V1 x L2	11
2	H1V1 x L1	11
	H1V1 x L2	12
	R3 x L1	12
	R3 x L2	17
	R2 x L1	14
	R2 x L2	22
	R1 x L1	15
	R1 x L2	21
	R0 x L1	12
	R0 x L2	14

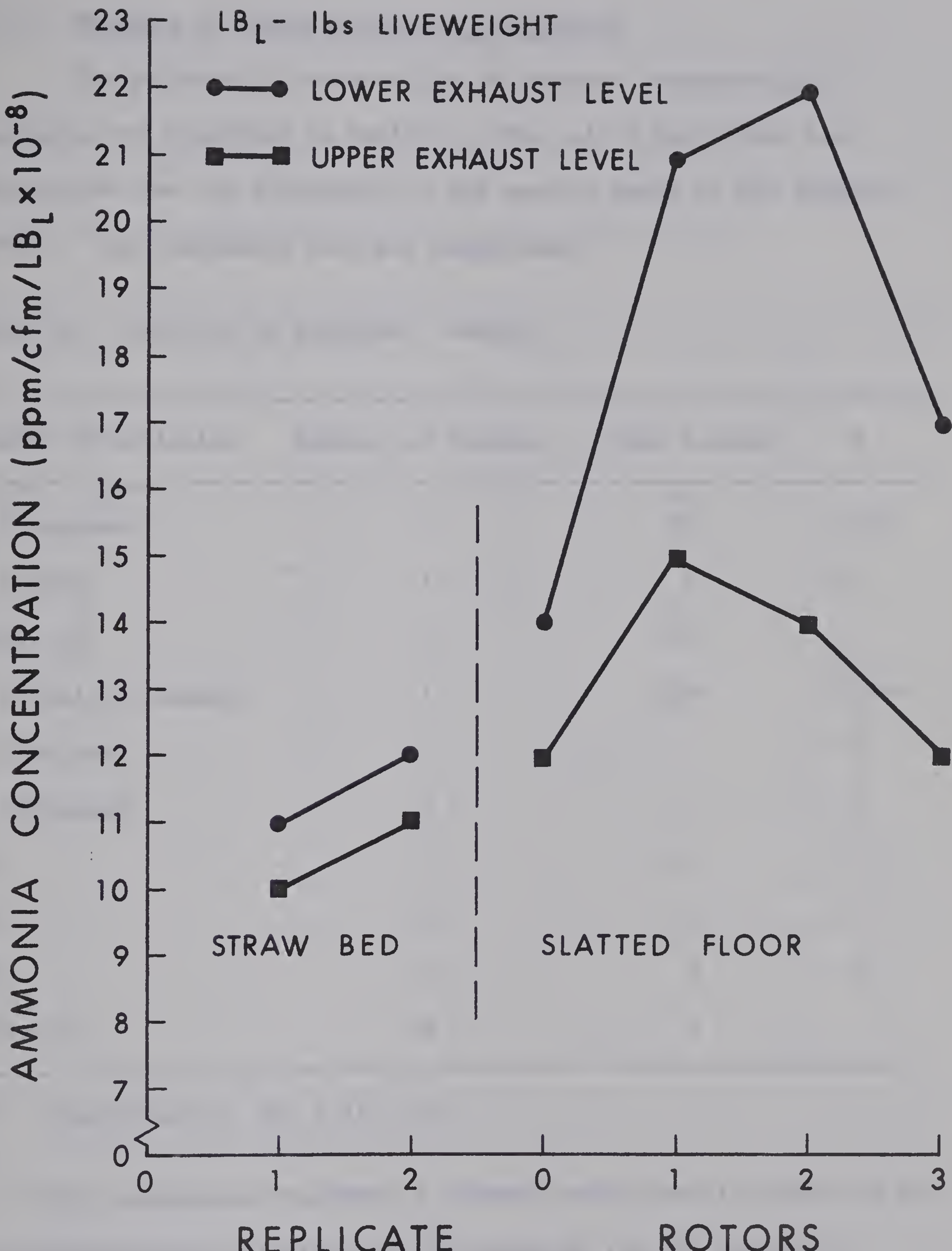


Figure 16. Graph illustrating the effect of the rotors in the slatted-floor housing system and the straw-bedded housing system on the ammonia removal rate at the two exhaust levels.

5.3.1 Analysis of Variance Results for Ammonia

The analysis of variance for the ammonia concentrations exhausted are presented in table 11. The only F value that was significant was the difference in the overall means of the exhaust levels. The treatments were not significant.

TABLE 11. ANALYSIS OF VARIANCE - AMMONIA

Source of Variation	Degrees of Freedom	Mean Squares	F
T (Treatment)	5	63	1.85
B (Block)	1	6	<1
Error (1)	5	34	
L (Level of exhaust)	1	238	47.6**
P (Period)	1	1	<1
S (Sequence)	1	1	<1
TL	5	12	2.4
TP	5	10	2
TS	5	3	<1
Error (2)	18	5	

** Significant at the 0.01 level.

The interaction treatment x exhaust level shown in figure 16 is not statistically different but is presented for the purpose of discussion.

5.4 EXPERIMENT 3 - CARBON DIOXIDE

This study was identical to that with ammonia except that CO_2 removal occurring for each treatment was taken into consideration.

The overall mean values for CO_2 removal are presented in table 12 and plotted on figure 17. In this case, the efficiency of CO_2 removal is expressed as ppm per 1000 cfm per 10,000 lb.

TABLE 12. MEAN EFFICIENCIES FOR CARBON DIOXIDE REMOVAL.

Treatment	CO_2 ppm/cfm/lb x 10^{-7}	Treatment	CO_2 ppm/cfm/lb x 10^{-7}
REP1 H1V1	130	REP1 H1V1 x L1	134
REP2 H1V1	146	REP1 H1V1 x L2	126
R3	109	REP1 H1V1 x L1	151
R2	129	REP2 H1V1 x L2	142
R1	120	R3 x L1	114
R0	120	R3 x L2	104
L1	126	R2 x L1	119
L2	125	R2 x L2	139
P1	130	R1 x L1	118
P2	121	R1 x L2	122
		R0 x L1	121
		R0 x L2	119

Overall mean efficiencies for CO_2 removal at the lower exhaust level were higher than those of the upper exhaust level except for the treatments of two and one operating rotors. As in the study with NH_3, the mean efficiencies for the treatments consisting of one and two operating rotors were higher than that of the treatment consisting of three rotors.

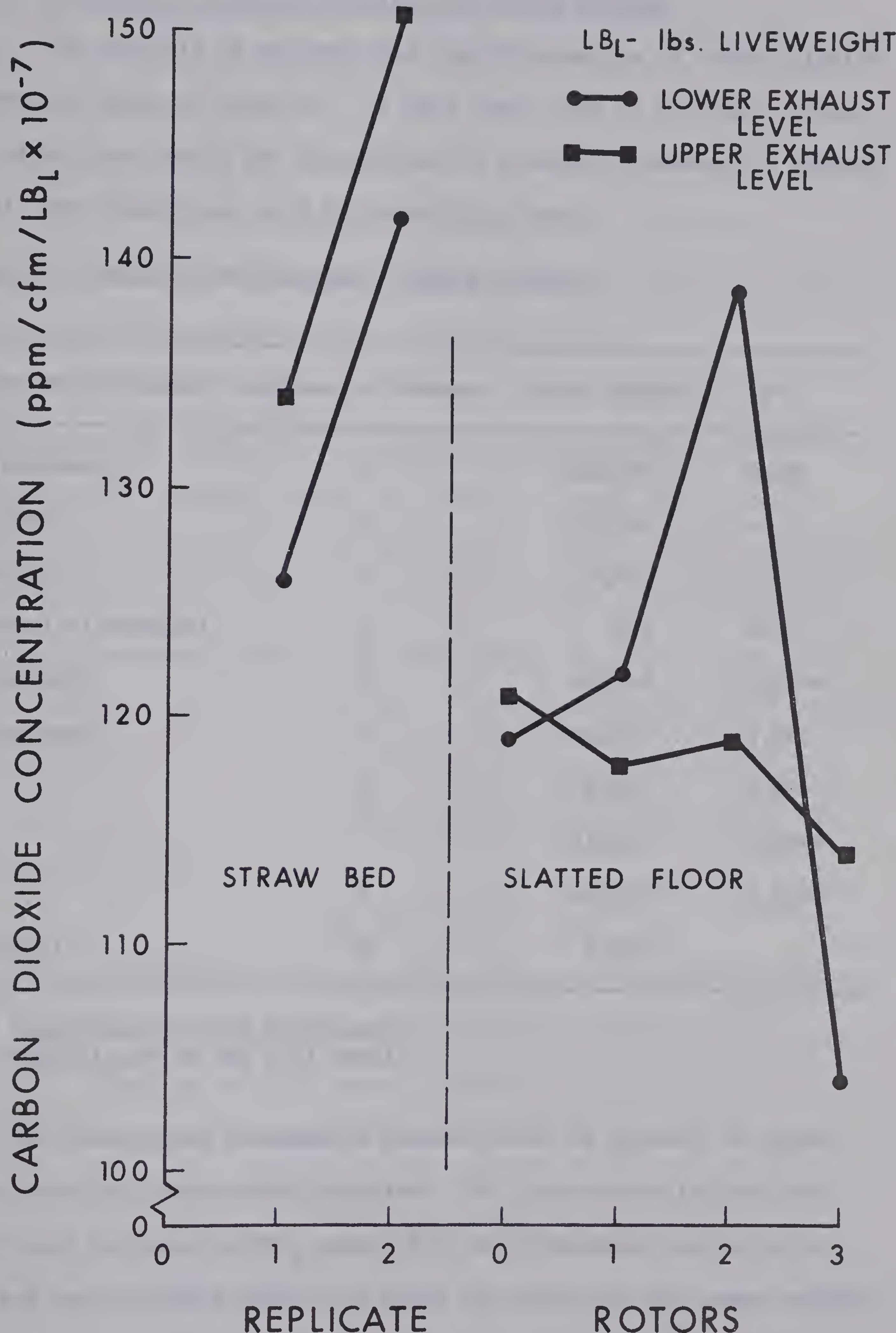


Figure 17. Graph illustrating the effect of the rotors in the slatted floor housing system and the straw-bedded housing system on the carbon dioxide removal rate at the two different exhaust levels.

5.4.1 Analysis of Variance Results for Carbon Dioxide

The analysis of variance for the efficiencies of carbon dioxide removal is shown in table 13. In this case, none of the main effects are significant while the interaction of interest, treatment x exhaust level, was significant at 0.05 probability level.

TABLE 13. ANALYSIS OF VARIANCE - CARBON DIOXIDE.

Source of Variation	Degrees of Freedom	Mean Squares	F
T (Treatment)	5	128,280	3.40
B (Block)	1	25,530	<1
Error (1)	5	37,695	
L (Level of exhaust)	1	581	<1
P (Period)	1	99,828	15.02**
S (Sequence)	1	26,555	3.99
TL	5	26,091	3.92*
TP	5	28,507	4.29**
TS	5	60,537	9.11**
Error (2)	18	6,642	

* Significant at the 0.05 level
** Significant at the 0.01 level

The interaction treatment x exhaust level is plotted in figure 17 to show the trends which occurred. The interaction follows the same trend as found for NH_3 except for the treatments consisting of two and one operating rotors, in which the effect of the upper exhaust level was greater than that of the lower level exhaust. Also the overall mean CO_2 concentration in the straw-bedded housing system

tended to be higher than that of the slatted-floor housing system whereas the ammonia concentrations tended to be lower in the former than in the latter system.

5.5 Multiple Regression

A Multiple Regression program (25) was used to determine how much of the variation in the dependent variables of interest, namely water vapour (WVR), ammonia (NH_3) and carbon dioxide (CO_2) removed could be accounted for by the following variables: ventilation rate, total animal weight for each treatment, relative humidity, inside ambient temperature, water consumption of the animals, and the number of operating rotors. Also included with these variables were their interactions and their linear transformations. The linear transformations of the independent variable X were: $(X)^{1/4}$, $(X)^{1/2}$, $(X)^2$, $(X)^3$ and $(X)^4$. The following regression equation includes only the main effects since inclusion of the interactions and linear transformations of these variables would have resulted in an unwieldy equation.

$$Y = A_0 + A_1V + A_2T + A_2R + A_3RH + A_4C + A_5A$$

where Y = dependent variable, WVR , NH_3 and CO_2 concentrations,

V = ventilation rate (cubic feet per minute x 10^{-3}),

T = temperature (degrees Fahrenheit (^oF) x 10^{-1}),

R = number of operating rotors,

RH = relative humidity (per cent),

C = consumption of animals (gallons x 10^{-2})

A = total animal weight for each housing system (pounds(lb) x 10^{-4})

A_0 = intercept, and

$A_1 \ldots A_5$ = multiple partial regression coefficients.

The regression equation for each treatment was derived by using a computer program (25) for a stepwise multiple regression. The purpose of these regression equations was to explain the variation that occurred within the data obtained. As a result, some of the equations are very complex. To explain the additional variation accounted for by each subsequent term in an equation, the proportion of the sums of squares reduced was calculated. The above variables were chosen since they could be measured on a practical basis.

5.5.1 Regression Analysis for Water Vapour Removal Rate

5.5.1.1 Slatted-Floor Housing System at the Lower Exhaust Level

The results of the regression analysis for this treatment indicated that animal weight and the temperature x relative humidity interaction accounted for 55.9 per cent of the variation in the WVR. The standard error of the estimate was 6.5 lb of water vapour per hr. The inclusion of the other variables reduced the error to 6.1 lb/hr. Table 15 shows the variation accounted for by each term in the regression equation. The overall results for the regression equation are given in table 14.

TABLE 14. REGRESSION ANALYSIS RESULTS FOR WATER VAPOUR REMOVAL RATE IN THE SLATTED-FLOOR HOUSING SYSTEM AT THE LOWER EXHAUST LEVEL.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Squares	F
Attributable to regression	4	1334.45	333.61	8.98**
Deviation from Regression	19	705.94	37.15	
Total	23	2040.39		

Regression Equation

$$Y = 221.95 - 158.69A^{1/4} + 1.04\ T \times RH - 0.93R^4 + 2.69R^3$$

Multiple Correlation Coefficient = 0.809

Cumulative Proportion of Sum of Squares Reduced = 0.654

Standard Error of Estimate = 6.1 lb/hr.

** Significant at the 0.01 level of probability.

TABLE 15: PROPORTION OF THE SUM OF SQUARES REDUCED AND THE STANDARD ERROR OF ESTIMATE FOR THE VARIABLES IN THE WATER VAPOUR REMOVAL RATE REGRESSION EQUATION FOR THE SLATTED-FLOOR HOUSING SYSTEM AT THE LOWER EXHAUST LEVEL.

Variable	Proportion of Sum of Squares Reduced %	Standard Error of Estimate lb/hr
$A^{1/4}$	41.4	7.4
T x RH	14.5	6.5
R^4	4.1	6.4
R^3	5.4	6.1

5.5.1.2 Slatted-Floor Housing System with Upper Exhaust Level

For this treatment, the regression analysis indicated that the independent variables A x RH, T^2, RH^4, RH^3 accounted for 57 per cent of the variation in the WVRR. The standard error of estimate was 6.8 lb of water vapour per hour. The remainder of the variables accounted for 37 per cent of the variation and reduced the standard error of estimate to 3.1 lb of water vapour per hour. The regression equation obtained is shown in table 16 while the proportion of the sum of squares reduced for each step are shown in table 17 with its respective standard error of estimate.

TABLE 16. REGRESSION ANALYSIS RESULTS FOR WATER VAPOUR REMOVAL RATE IN THE SLATTED-FLOOR HOUSING SYSTEM AT UPPER EXHAUST LEVEL.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Squares	F
Attributable to regression	11	1910.74	173.70	18.13**
Deviation from regression	12	114.95	9.58	
Total	23	2025.69		

Regression Equation

$$Y = 9203.29 - 17.36A \times RH - 6.06T^2 - 4.78RH^4 + 63.29RH^3$$
$$- 2782.58RH + 15.32T \times RH + 7.10V \times A - 18.39R^4$$
$$+ 105.01R^3 - 174.99R^2 + 22.24\ A \times R$$

Multiple Correlation Coefficient = 0.971

Cumulative Proportion of Sum of Squares Reduced = 0.943

Standard Error of Estimate = 3.1 lb/hr

** Significant at the 0.01 level of probability.

TABLE 17. PROPORTION OF THE SUM OF SQUARES AND THE STANDARD ERROR OF ESTIMATE FOR THE VARIABLES IN THE WATER VAPOUR REMOVAL RATE REGRESSION EQUATION FOR THE SLATTED-FLOOR HOUSING SYSTEM AT THE UPPER EXHAUST LEVEL.

Variable	Proportion of Sum of Squares Reduced %	Standard Error of Estimate lb/hr
A x RH	10.9	9.0
T^2	24.0	7.9
RH^4	01.6	8.0
RH^3	20.5	6.8
RH	05.2	6.5
T x RH	04.8	6.3
V x A	03.9	6.1
R^4	04.2	5.8
R^3	03.6	5.5
R^2	09.7	4.2
A x R	05.9	3.1

5.1.1.3 Straw-Bedded Housing System with Upper Exhaust Level

The regression analysis for this treatment showed that $T \times V$, $(A)^4$, RH^4 accounted for 49 per cent of the variation in the independent variable with a standard error of estimate of 7.8 lb of water vapour per hour. The insertion of the other variables accounted for an additional 36 per cent of the variation while the standard error of estimate was reduced to 4.8 lb of water vapour per hour. The results for the regression equation is given in table 18 while table 19 gives the proportion of sum of squares reduced for each step and the standard error of estimate for each term entered into the equation.

TABLE 18. REGRESSION ANALYSIS RESULTS FOR WATER VAPOUR REMOVAL RATE IN THE STRAW-BEDDED HOUSING SYSTEM AT UPPER EXHAUST LEVEL.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Squares	F
Attributable to regression	7	2056.80	293.83	12.88**
Deviation from regression	16	364.88	22.80	
Total	23	2421.67		

Regression Equation

$$Y = 371.46 + 41.50T \times V - 6.89A^4 + 0.024RH^4 + 36.95A^3$$
$$- 2.41T \times RH - 84.70V \times A - 115.10T$$

Multiple Correlation Coefficient = 0.922

Cumulative Proportion of Sum of Squares Reduced = 0.849

Standard Error of Estimate = 4.8 lb/hr

** Significant at the 0.01 level of probability.

TABLE 19. PROPORTION OF THE SUM OF SQUARES AND THE STANDARD ERROR OF ESTIMATE FOR THE VARIABLES IN THE WATER REMOVAL RATE REGRESSION EQUATION FOR THE STRAW-BEDDED HOUSING SYSTEM AT THE UPPER EXHAUST LEVEL.

Variable	Proportion of Sum of Squares Reduced %	Standard Error of Estimate lb/hr
T x V	23.4	9.2
A^4	14.6	8.5
RH^4	11.1	7.8
A^3	08.7	7.3
T x RH	04.3	7.1
V x A	11.4	6.1
T	11.4	4.8

5.5.1.4 Straw-Bedded Housing System with Lower Exhaust Level

The results of the regression analysis for the water vapour removal rate are given in table 20. In this case, the terms $T^{1/4}$, T x V, A^4 and $RH^{1/4}$ accounted for 43 per cent of the variation in

the dependent variable. The inclusion of the other terms increased the explained variation to 84.7 per cent. The standard error estimate was reduced from 7.3 to 4.6 lb of water vapour per hour. Table 21 gives the values for the variation explained in each of the variables entered into the equation and the standard error of estimates.

TABLE 20. REGRESSION ANALYSIS RESULTS FOR WATER VAPOUR REMOVAL RATE IN THE STRAW-BEDDED HOUSING SYSTEM AT THE LOWER EXHAUST LEVEL.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Squares	F
Attributable to regression	10	1501.50	150.15	7.22**
Deviation from regression	13	270.34	20.79	
Total	23	1771.84		

Regression Equation

$$Y = -3176.64 - 1804.52T^{1/4} + 42.64T \times V + 4.87A^{4} + 719.30RH^{1/4} - 39.95V \times RH + 760.77V + 22.72C \times RH - 42.40C \times V - 229.81V \times A + 3254.15A^{1/4}$$

Multiple Correlation Coefficient = 0.921

Cumulative Proportion of Sum of Squares Reduced = 0.847

Standard Error of Estimate = 4.6 lb/hr

** Significant at the 0.01 level of probability.

TABLE 21. PROPORTION OF THE SUM OF SQUARES AND THE STANDARD ERROR OF ESTIMATE FOR THE VARIABLES IN THE WATER VAPOUR REMOVAL RATE REGRESSION EQUATION FOR THE STRAW-BEDDED HOUSING SYSTEM AT THE LOWER EXHAUST LEVEL.

Variable	Proportion of Sum of Squares Reduced %	Standard Error of Estimate lb/hr
$T^{1/4}$	25.8	7.7
T x V	01.8	7.8
A^4	10.2	7.4
$RH^{1/4}$	05.2	7.3
V x RH	29.9	5.2
V	01.7	5.1
C x RH	01.0	5.2
C x V	01.5	5.2
V x A	00.7	5.3
$A^{1/4}$	06.9	4.6

5.5.2 Regression Analysis for Ammonia

In this analysis, only the slatted-floor housing system was considered since no significant part of the variation occurring in the dependent variable (NH_3) could be accounted for within the straw-bedded housing. It should be noted that the relationship or correlation between NH_3 and CO_2 was also of interest.

5.5.2.1 Slatted-Floor Housing System at the Lower Exhaust Level

In this treatment, the interaction CO_2 x RH and $R^{1/4}$

attributed towards 53 per cent of the variation. The remainder of the terms accounted for an additional 32 per cent of the variation in the dependent variable. The inclusion of the remaining variables reduced the standard error of estimate from 2.8 to 1.8 ppm of NH_3. Table 23 gives the percentage of the variation accounted for by each successive term in the regression equation given in table 22.

TABLE 22. REGRESSION ANALYSIS RESULTS FOR AMMONIA REMOVAL IN THE SLATTED-FLOOR HOUSING SYSTEM AT LOWER EXHAUST LEVEL.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Squares	F
Attributable to regression	5	180.04	36.01	11.21**
Deviation from regression	10	32.12	3.21	
Total	15	212.16		

Regression Equation

$$Y = -44.48 - 0.544CO_2 \times RH + 14.88R^{1/4} + 1.40CO_2 \times A$$
$$+ 0.92T \times V + 0.57T \times RH$$

Multiple Correlation Coefficient = 0.921

Cumulative Proportion of Sum of Squares Reduced = 0.849

Standard Error of Estimate = 1.8 ppm

** Significant at the 0.01 level of probability.

TABLE 23. PROPORTION OF THE SUM OF SQUARES AND THE STANDARD ERROR OF ESTIMATE FOR THE VARIABLES IN THE AMMONIA REGRESSION EQUATION FOR THE SLATTED-FLOOR HOUSING SYSTEM AT THE LOWER EXHAUST LEVEL.

Variable	Proportion of Sum of Squares Reduced %	Standard Error of Estimate ppm
$CO_2 \times RH$	35.8	3.1
$R^{1/4}$	17.4	2.8
$CO_2 \times A$	20.7	2.1
$T \times V$	07.0	1.9
$CO_2 \times A$	03.9	1.8

5.5.2.2 Slatted-Floor Housing at the Upper Exhaust Level

In this case, the variables $(R)^4$, $(RH)^{1/4}$, and RH explained 54 per cent of the variation occurring in the NH_3 concentrations being removed. The remaining variables accounted for only a negligible amount of the remaining variation such that the number of terms within the equation was terminated at this point. The regression analysis is described in table 24. The variation in the dependent variable accounted for by each term is shown in table 25.

TABLE 24. REGRESSION ANALYSIS FOR AMMONIA REMOVAL IN THE SLATTED-FLOOR HOUSING AT THE UPPER EXHAUST LEVEL.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Squares	F
Attributable to regression	3	67.42	22.47	4.71**
Deviation from regression	12	57.31	4.78	
Total	15	124.73		

Regression Equation

$$Y = -5576.87 - 0.0592R^4 + 4711.49RH^{1/4} - 297.32RH$$

Multiple Correlation Coefficient = 0.735

Cumulative Proportion of Sum of Squares Reduced = 0.540

Standard Error of Estimate = 2.2 ppm

** Significant at the 0.01 level of probability.

TABLE 25. PROPORTION OF SUM OF SQUARES AND THE STANDARD ERROR OF ESTIMATE FOR THE VARIABLES IN THE AMMONIA REGRESSION EQUATION FOR THE SLATTED-FLOOR HOUSING SYSTEM AT THE UPPER EXHAUST LEVEL.

Variable	Proportion of Sum of Squares Reduced %	Standard Error of Estimate ppm
R^4	34.9	2.4
$RH^{1/4}$	06.5	2.4
RH	12.6	2.2

5.5.3 Regression Analysis for Carbon Dioxide

In this analysis, the two exhaust levels in the straw-bedded housing unit were combined into one treatment since the differences between these two treatments were not significant as determined by the analysis of variance. The ammonia concentration being removed was added as an independent variable to determine its degree of correlation with the carbon dioxide removal.

5.5.3.1 Slatted-Floor Housing System at the Upper Exhaust Level

The regression analysis carried out in this treatment is described in table 26 while the variation accounted for by each term is explained in table 27 with each respective standard error of estimate. The interaction V x R accounted for 81 per cent of the variation in the mean CO_2 concentration being removed. The other terms included in the equation accounted for 9 per cent of the variation. The standard error of estimate was reduced from 65.0 to 51.4 ppm.

TABLE 26. REGRESSION ANALYSIS FOR CARBON DIOXIDE REMOVAL IN THE SLATTED-FLOOR HOUSING SYSTEM AT THE UPPER EXHAUST LEVEL.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Squares	F
Attributable to regression	3	27.66	9.22	34.87**
Deviation from regression	12	3.17	0.26	
Total	15	30.83		

Regression Equation

$$Y = -23.95 - 0.39\ V \times R + 25.47 RH^{1/4} - 0.198 T \times V$$

Multiple Correlation Coefficient = 0.947

Cumulative Proportion of Sum of Squares Reduced = 0.897

Standard Error of Estimate = 51.4 ppm

** Significant at the 0.01 level of probability.

TABLE 27. PROPORTION OF THE SUM OF SQUARES AND THE STANDARD ERROR OF ESTIMATE FOR THE VARIABLES IN THE CARBON DIOXIDE REGRESSION EQUATION FOR THE SLATTED-FLOOR SYSTEM HOUSING AT UPPER EXHAUST LEVEL.

Variable	Proportion of Sum of Squares Reduced %	Standard Error of Estimate ppm
V x R	80.8	65.0
$RH^{1/4}$	05.5	57.0
T x V	03.4	51.4

5.5.3.2 Slatted-Floor Housing System at Lower Exhaust Level

The results for the regression analysis of this treatment are presented in table 28.

In this treatment, the regression analysis indicated that 77 per cent of the variation for the CO_2 concentration being removed was explained by R^4 and the interaction T x RH. The remaining terms accounted for 15 per cent of the variation. The standard error of estimate for the entire equation was 74.0 ppm while the first two terms in the equation increased the standard error to 98.7 ppm. The variation accounted for by each term and the cumulative standard error of estimate is presented in table 29.

TABLE 28. REGRESSION ANALYSIS RESULTS FOR CARBON DIOXIDE REMOVAL IN THE SLATTED-FLOOR HOUSING SYSTEM AT THE LOWER EXHAUST LEVEL.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Squares	F
Attributable to regression	7	51.78	7.40	13.52**
Deviation from regression	8	4.38	0.55	
Total	15	56.15		

Regression Equation

$$Y = 113.08 - 0.07R^4 + 0.38T \times RH - 0.60A \times RH + 0.464NH_3 \times A - 0.035NH_3^{\,2} - 88.28A^{1/4} - 1.67R^{1/4}$$

Multiple Correlation Coefficient = 0.960

Cumulative Proportion of Sum of Squares Reduced = 0.922

Standard Error of Estimate = 74.0 ppm.

** Significant at the 0.01 level of probability.

TABLE 29. PROPORTION OF SUM OF SQUARES AND THE STANDARD ERROR OF ESTIMATE FOR THE VARIABLES IN THE CARBON DIOXIDE REGRESSION EQUATION FOR THE SLATTED-FLOOR HOUSING SYSTEM AT THE LOWER EXHAUST LEVEL.

Variable	Proportion of Sum of Squares Reduced %	Standard Error of Estimate ppm
R^4	68.0	113.2
T x RH	09.4	98.7
A x RH	08.3	81.8
NH_3 x A	02.0	79.3
NH_3^2	01.5	77.8
$A^{1/4}$	01.7	75.5
$R^{1/4}$	01.3	74.0

5.3.3.3 Straw-Bedded Housing System

The results of the regression analysis for carbon dioxide are given in table 30. The regression analysis for the treatment indicated that the variables $A^{1/4}$ and NH_3 contributed 86 per cent towards the variation of the dependent variable. The inclusion of the other terms increased the coefficient of determination to 90.5 per cent. The standard error of estimate did not change with the insertion of the remaining vairables. The standard error of estimate and the proportion of the sum of squares reduced by each term is shown in table 31.

TABLE 30. REGRESSION ANALYSIS RESULTS FOR CARBON DIOXIDE REMOVAL IN THE STRAW-BEDDED HOUSING SYSTEM.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Squares	F
Attributable to regression	6	48.70	8.12	14.12**
Deviation from regression	9	5.17	0.57	
Total	15	53.87		

Regression Equation

$$Y = -50.06 + 51.56A^{1/4} - 0.00069NH_3^{\,4} - 0.1103T \times RH$$
$$- 0.440NH_3 \times T + 0.26NH_3^{\,2} + 0.448T \times V$$

Multiple Correlation Coefficient = 0.951

Cumulative Proportion of Sum of Squares Reduced = 0.904

Standard Error of Estimate = 75.8 ppm

** Significant at the 0.01 level of probability.

TABLE 31. PROPORTION OF THE SUM OF SQUARES AND THE STANDARD ERROR OF ESTIMATE FOR THE VARIABLES IN THE CARBON DIOXIDE EQUATION FOR THE STRAW-BEDDED HOUSING SYSTEM.

Variable	Proportion of Sum of Squares Reduced %	Standard Error of Estimate ppm
$A^{1/4}$	81.0	85.5
$NH_3^{\ 4}$	05.0	76.3
T x RH	01.2	76.0
NH_3 x T	00.8	76.8
$NH_3^{\ 2}$	01.3	76.2
T x V	01.2	75.8

It should be noted that the above regression equations are presented for the sole purpose of comparing the trends which occurred between the treatments. The tables presenting the proportion of sum of squares reduced and the standard error of estimate for each variable or interaction are given to enable the equations to be used on a practical basis. The number of terms to be included in the regression equations for the purpose of practical significance can be determined from these tables.

5.6 Moisture Balance.

As mentioned in the experimental procedure, an attempt was made to determine the moisture balance for each housing system. The moisture balance included the following parameters;

a) Moisture entering and leaving the housing system via the exchange air.

b) Water consumption of the animals.

c) Moisture content of the feed fed to the animals.

d) Accumulation of moisture in the pits or straw bed.

e) The moisture retained by the animals.

Since the liveweight gain constitutes 70 per cent water (9), the moisture retained due to liveweight gain was estimated for each period. The factors considered in the moisture balance were all expressed in lb per animal per day. The average values for the above factors were obtained from Appendix 8 and tabulated in table 32.

The following formulae were used to establish the water balance.

wvrr = Wo - Wi

where wvrr = Water vapour removed by exchange air, lb per animal per day,

Wo = Water vapour exhausted, lb per animal per day, and

Wi = Water Vapour entering, lb per animal per day.

The water vapour removed (wvr) was expressed in terms of lb per 1000 lb liveweight per day and in lb per animal per day.

wvrr + Z + R = C + F

where Z = moisture accumulated in the pits or straw bed (measured) lb per animal per day,

R = moisture retained by the animals, lb per animal per day,

C = water consumption of the animals, lb per animal per day, and

F = moisture content of the feed, lb per animal per day.

The error existing in the moisture balance was expressed in the following equation.

$$E = C + F - wvrr - Z - R$$

where E = Error existing in the moisture balance, lb per animal per day.

The error term could be due to the inaccuracy of the temperature readings with respect to the dry and wet-bulb thermocouples, the water meters, the determination of the moisture content in the feed and the measurement of the moisture accumulating in the pits or the straw bed. It was felt that the major part of any error would exist in determination of the accumulated moisture within the housing system. The reason for this view was that the increase in accumulated moisture during each trial run was very small relative to the original amount of moisture present in the pits or in the straw bed. As a result, the moisture accumulated during each trial run also was calculated by the following formula.

$$Y = C + F - wvrr - R$$

where Y = calculated accumulation of moisture, lb per animal per day. This value served as a comparison with the observed or measured amount of accumulated moisture.

From the data presented in table 32, several trends were noted. The percentage error occurring in the determination of the moisture balance which was based on total moisture input, ranged from 2.0 to 16.5 per cent. Also of interest was the water vapour removed per

TABLE 32. SUMMARY DATA: MOISTURE BALANCE FOR THE TWO HOUSING SYSTEMS.

Housing	Slatted-Floor Housing								Straw-Bedded Housing	
Treatment	3 Rotors		2 Rotors		1 Rotor		No Rotors			
Exhaust Level	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper
Average animal weight, lb	644	644	761	761	823	823	885	885	640	640
Average temperature, °F	59	59	63	62	61	61	67	68	60	60
Average relative humidity, %	70	66	69	64	66	61	62	62	64	66
Average ventilation rate, cfm	3032	3060	3032	3060	3032	3060	3032	3060	2943	2992
Average ventilation rate per animal, cfm/an	79.8	80.5	79.8	80.5	79.8	80.5	79.8	80.5	79.5	80.9
Moisture entering, lb/an/day	28.3	32.1	32.2	31.2	34.6	36.5	46.7	47.0	29.6	32.8
Moisture exhausted, lb/an/day	68.6	66.4	74.5	66.3	68.1	63.4	79.4	81.7	64.8	66.0
Water consumed, lb/an/day	47.0	47.4	53.5	50.0	52.5	51.5	60.0	65.0	50.0	52.0
Moisture in Feed, lb/an/day	7.6	7.7	5.5	5.1	4.8	5.7	5.9	5.9	7.5	7.3
Moisture retained by animal, lb/an/day	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3
Moisture accumulation, lb/an/day	21.0	26.0	20.1	23.5	31.3	29.0	30.0	40.0	30.7	25.3
Calculated accumulation, lb/an/day	12.0	18.4	14.3	17.2	28.0	27.9	30.9	34.0	20.4	23.3
Error in moisture balance, lb/an/day	9.0	7.5	6.0	6.6	3.3	0.9	-1.2	6.1	1.0	2.0
Percentage error of total input, lb/an/day	16.5	13.6	10.2	12.0	5.7	2.0	2.0	8.6	1.7	3.4
Water vapour removal rate, wvr/an/day	40.3	34.3	42.3	35.1	33.5	26.9	32.7	34.7	35.2	33.2
Water vapour removal rate, wvr/an/hour	1.67	1.43	1.76	1.46	1.39	1.12	1.36	1.44	1.46	1.38
Water vapour removal rate, wvr/1000 lb/day	62.6	53.3	55.6	46.1	40.7	32.7	36.9	39.2	55.0	51.9
Percentage of moisture removed, %	73	62	72	63	58	47	49	48	61	55

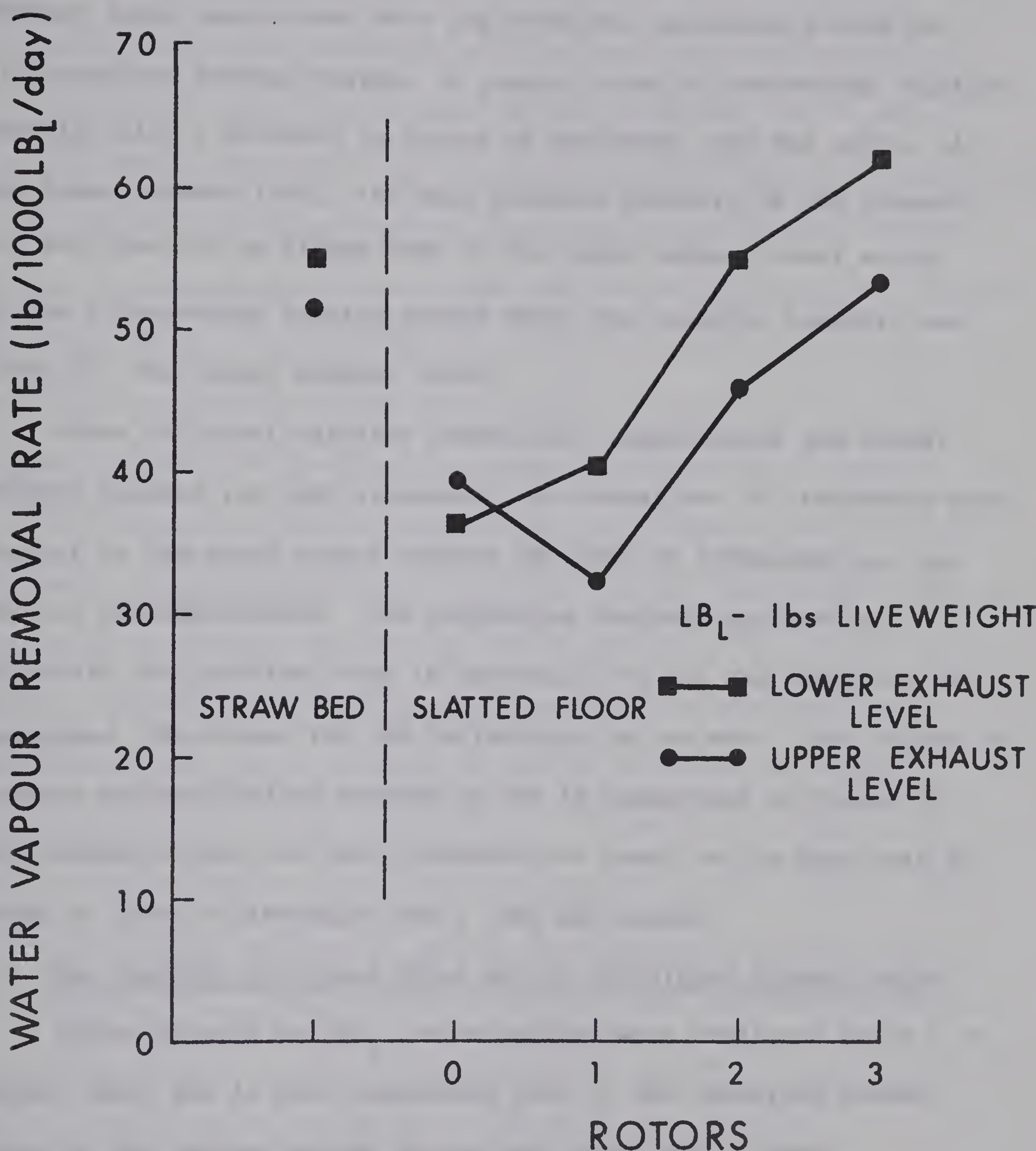


Figure 18. A graphical comparison showing the effect of housing and exhaust levels on water vapour removal rate.

1000 lb of liveweight per day. As would be expected, this figure decreased as the number of rotors operating decreased. With respect to exhaust levels, the figure was found to be greater at the lower exhaust level except when only one rotor was operating within the slatted-floor housing system. A general trend of decreasing relative humidity with a decrease in rotors in operation also was noted. At the lower exhaust level, the mean relative humidity of the exhaust air was found to be higher than at the upper exhaust level except in the straw-bedded housing system where the relative humidity was lower for the former exhaust level.

Since different relative humidities, temperatures and animal weights existed for each treatment, the comparison of treatments with respect to the water vapour removed per 1000 lb liveweight per day was not straightforward. The regression analysis appeared to alleviate this problem since it accounted for all the variables and explained the reason for the variability in the wvrr. The effect of housing and ventilation systems on wvr is summarized in figure 18. The plotted values for each treatment are based on the mean wvrr in terms of 1000 lb liveweight and a one day period.

5.7 Gas Sampling at Animal Level and in Individual Exhaust Ducts.

Carbon dioxide and NH_3 concentrations were monitored twice - at animal level and in each individual duct of the operating exhaust level of the housing system during each trial run. These concentrations were then compared with that of the main exhaust duct as presented in table 33. To determine the NH_3 and CO_2 produced by the animals and their wastes, the mean inlet concentrations for each housing system were subtracted from the concentrations of their

respective main exhaust duct. These values were based on the hourly data obtained during the experiment (Appendix 9).

As shown in table 33, the mean NH_3 concentrations produced in the straw-bedded housing system tended to be less than that produced in the slatted-floor housing system. The NH_3 concentration at animal level tended to be the same as or slightly higher than the concentration of the exhaust air except at the lower exhaust level in the slatted-floor housing system. In this case, the concentration of NH_3 at animal level was found to be less than that of the exhausted air (figures 19 and 20). It should be noted that the NH_3 existing in each housing system was small relative to the threshold limit of 100 ppm (6).

With regard to the CO_2 production per animal, it was found that the mean concentrations produced in the slatted-floor housing system tended to be slightly higher than that produced in the other housing system. The CO_2 monitored in the straw-bedded housing system was somewhat higher due to the higher concentrations of CO_2 being introduced by the ventilation system. The reason for this was the fact that the mean ambient temperature was higher for this housing system; thus there was a greater CO_2 output from the in-duct heater because of the additional supplemental heat required. For each housing system, the amount of CO_2 at animal level tended to exceed the quantity of CO_2 in the exhausted air (figures 19 and 20).

The concentration differences between NH_3 and CO_2 of the individual ducts of each exhaust level were small except at the upper level in the slatted-floor housing system. In this case, the mean concentrations of the CO_2 in the west duct exceeded that of the east duct for each reading taken. The reason for this was most probably

due to the fact that the restricted area in which the animals were confined did not occupy the space under the east duct. This factor had no noticeable effect on the NH_3 exhausted. The main source or site of production of each gas was not, of course, the same and this fact obviously had a bearing in this regard.

The CO_2 input to the housing compartments increased with decreasing outside air temperatures since more supplemental heat was required. It was found that, at -25°F, the furnace would release approximately 1700 ppm of CO_2 to maintain a room temperature of 60°F. It should be noted that this amount includes the 300 ppm of CO_2 of the outside air. Therefore, the concentration of the CO_2 within each housing system approached 3000 ppm during these cold periods.

TABLE 33. SUMMARY OF THE MEAN AMMONIA AND CARBON DIOXIDE CONCENTRATIONS.

Housing System	Ammonia Slatted		Ammonia Straw-bedded		Carbon Dioxide Slatted		Carbon Dioxide Straw-bedded	
Exhaust Level	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper
Inlet, ppm	4	4	3	3	1110	1060	1500	1300
Outlet, ppm	21	16	11	11	1970	1960	2300	2150
Animal level, ppm	15	17	12	13	2150	2150	2500	2500
East duct, ppm	19	15	12	10	1950	1900	2330	2150
West duct, ppm	21	17	11	11	1970	1990	2360	2150
Animals and Waste, ppm	17	12	8	8	860	900	800	850
Animals and Waste, cubic ft/~~animal~~ day	74	53	34	34	3760	3930	3400	3630
Animals and Waste, cubic ft/animal/day	2	1	1	1	100	105	90	99

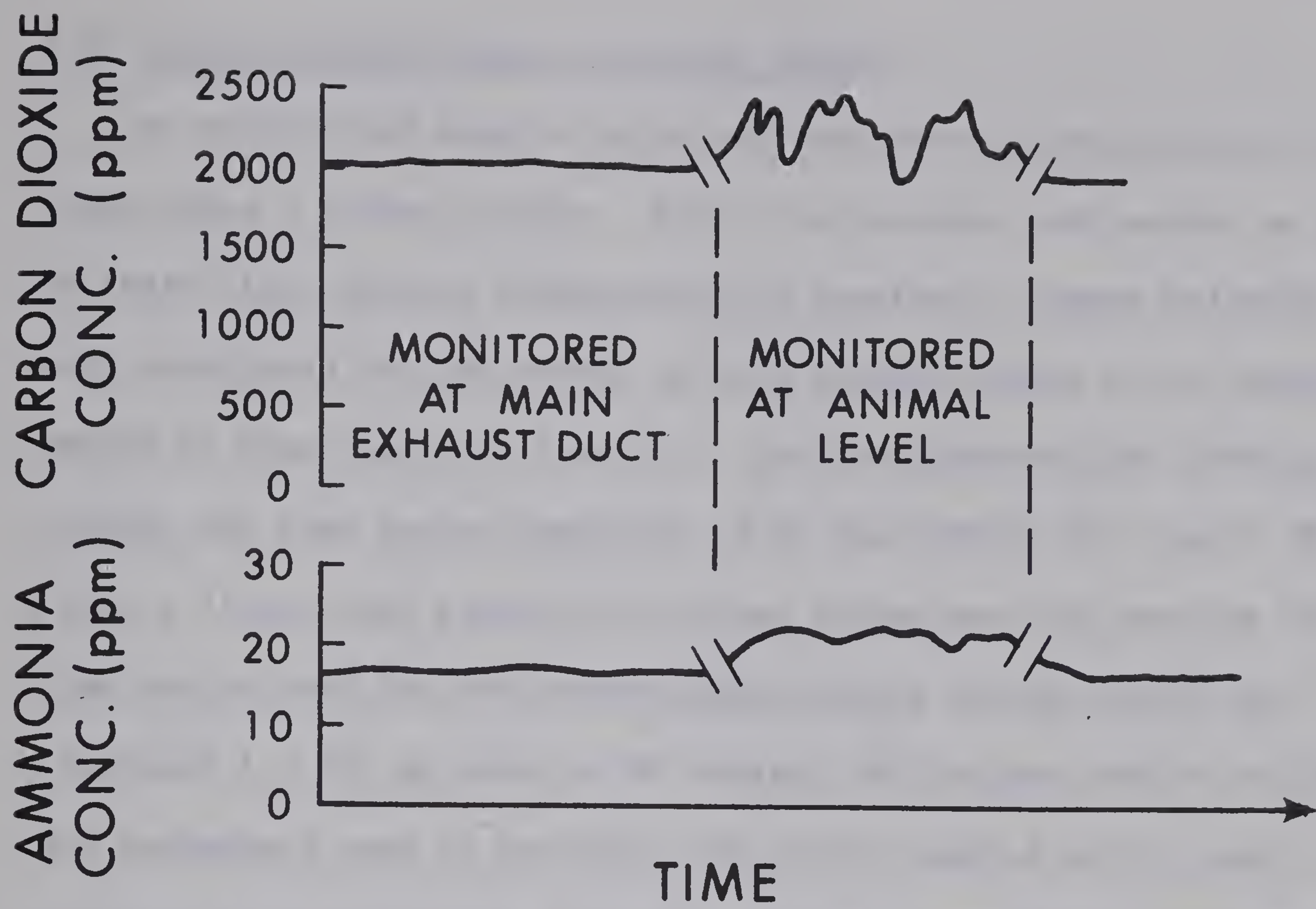


Figure 19. A graphical representation of a typical recording of ammonia and carbon dioxide concentrations at the upper exhaust level in the slatted-floor housing system.

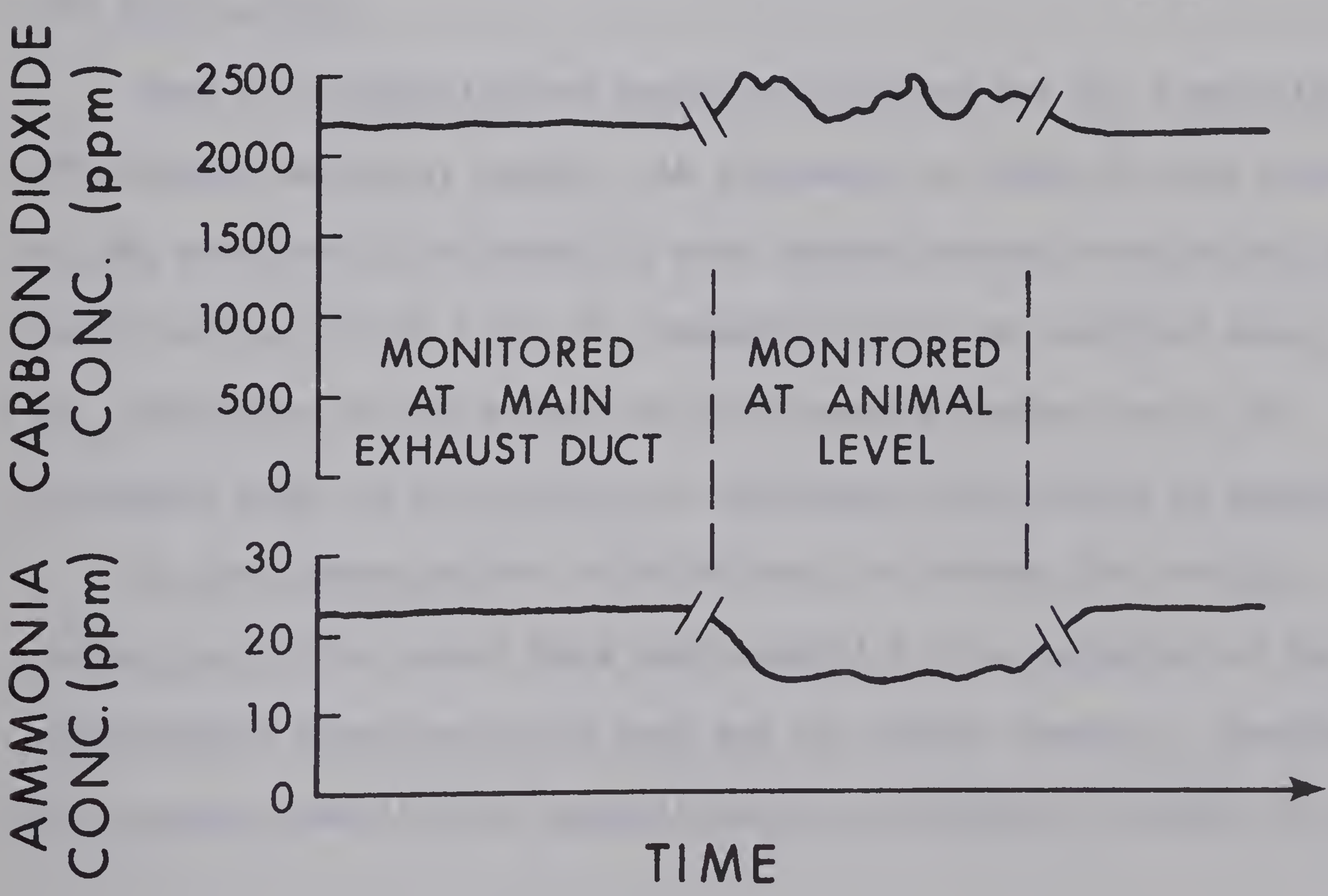


Figure 20. A graphical representation of a typical recording of ammonia and carbon dioxide concentrations at the lower exhaust level in the slatted-floor housing system.

5.8 Carbon Dioxide Output of a Beef Animal.

An attempt was made to calculate the carbon dioxide output of a steer using a carbon balance. Such a calculation only serves as an estimate since several assumptions are required. Carbon balances were calculated for the steers in each housing system for a certain period of time (Appendix 3 and 4). For the slatted-floor housing system, the time period consisted of 40 days (March 18 - April 28) in which a 75 per cent barley:25% haylage ration was fed, whereas the time period used for the straw-bedded housing system was 20 days (February 4 - 24) in which a 50% barley: 50% haylage ration was fed. The parameters used to determine the carbon expired as CO_2 were obtained from references (9,43,53). Animal liveweights, gain per day, feed intake, ventilation rate and monitored CO_2 values were averaged for each period.

Mean CO_2 concentrations monitored included the CO_2 production of the animals and their wastes. As presented in table 34, the amount of CO_2 produced by an animal in each housing system constitutes the major portion of the total CO_2 produced within the confined area. The CO_2 production of the animals in each housing system also is in agreement with the CO_2 expired by fattening cattle cited by Baxter (6).

In the carbon balance calculations, the values for the CO_2 production of the steers were most sensitive to a variation of the carbohydrate fraction of the feed and its carbon content. Therefore, an accurate quantitative analysis would be necessary in order to attain

a high degree of precision. The calculated concentration of CO_2 based on CO_2 expired by the animal are based on the average ventilation rates (table 34).

The difference between CO_2 production of the animals in each housing system was found to be only 4 ppm per animal. In terms of cubic feet, each steer in the straw-bedded housing system produced 11 cubic feet of CO_2 more per day than a steer in the slatted floor housing. The average weight of the steers in the straw-bedded housing system was 710 lb while the steers in the slatted-floor housing system averaged 870 lb for their respective period of study.

No literature was found which cited CO_2 production of anaerobic and aerobic decomposition of the beef cattle wastes at environmental temperatures. Gramms et al (24) undertook an extensive study on anaerobic digestion of dairy bull wastes at a digestion temperature of 90°F and a detention time ranging from 12 to 15 days. Using this data and the volatile solids production of beef animals cited by Aasen (1), CO_2 production per animal from the wastes was estimated. Gramms et al (24) found that approximately 5.17 cubic feet of gases were produced per pound of volatile solids destroyed per day of which 0.35 cubic feet were CO_2. A beef animal weighing 1000 pounds produces seven pounds of volatile solids per day of which 21.4 per cent are reduced (1,24). From this data, a daily production of CO_2 of 2.7 cubic feet would be anticipated. This figure suggests that the CO_2 production from the wastes is relatively small with respect to the CO_2 production of the steers.

The accuracy of the CO_2 analyzer was $\pm$100 ppm which is the equivalent to $\pm$11 cubic feet per day under these ventilation

conditions. Taking this into account, the recorded and the calculated CO_2 concentrations were found to be approximately equal. Therefore, the CO_2 production from the animal wastes in this experiment was very small relative to that from the animals, irrespective of whether the wastes were in the form of a manure pack or liquid slurry.

TABLE 34. CARBON BALANCE FOR STEERS IN TWO HOUSING SYSTEMS.

	Straw-bedded Housing System	Slatted-floor Housing System
Average weight of steer, lb	710	870
Number of animals	37	38
Average gain, lb/day	2.7	2.7
Measured CO_2 removal, ppm/animal	30.1 ± 3	31.9 ± 3
Measured CO_2 removal, cfd/animal	129 ± 11	139 ± 11
Average ventilation rate, cfm	2968	3030
Carbon in feed, lb/day	5.83	5.43
Carbon retained, lb/animal/day	0.41	0.41
Carbon expired, lb/animal/day	5.42	5.02
CO_2 expired, cfd/animal	146	135
CO_2 concentration, ppm	34.1	31.0

6. DISCUSSION

The purpose of the project was to determine the effect of housing systems and exhaust levels or heights on the water vapour and noxious gas removal rates. In these two housing systems, the floor design differed in that one was slatted while the other was straw-bedded. Both housing systems included two exhaust levels in which one exhausted the stale air below or at floor level while the other exhausted above the animals as commonly found in practice. In the slatted-floor housing system, the effect of the number of operating rotors on the water vapour and gas removal rates were studied, while in the straw-bedded housing system, the effect of the two different ventilation rates on the WVRR was studied. In the lower ventilation rate treatment in the straw-bedded housing system, the water vapour and gas removal rates were measured and used as a comparison with the treatments considered in the slatted-floor housing system.

6.1 Mean Water Vapour Removal Rates.

Three treatments were considered in determining their effect on the WVRR at each exhaust level. These included the comparison of the housing systems, two ventilation rates and the number of rotors in operation. The overall mean WVRR values were not significantly affected by the housing systems. However, the differences due to the exhaust levels were highly signficant for both housing systems with a greater WVRR occurring for the lower exhaust level. The WVRR was approximately the same at the upper exhaust level in both housing systems but the WVRR was greater in the slatted-floor housing system than in the straw-bedded housing system at the lower exhaust level as indicated by the significant interaction exhaust level x housing

(figure 13).

These results would suggest that the exhausting locations for a high level pressurized ventilation system should be evenly distributed along the wall beneath the floor in the slatted-floor housing system and at floor level in the straw-bedded housing system such that the water vapour is exhausted nearest to the site of production. It must be noted that three rotors were operating in the slatted-floor housing system during this time.

In the study of the two ventilation rates in the straw-bedded housing system, the ventilation rate was found to have a highly significant effect on the mean WVRR values. The interaction ventilation rate x exhaust level was insignificant but illustrated the fact (a) that the WVRR tended to be higher with the lower exhaust level operating and (b) that the WVRR was less at the higher ventilation rate. The mean RH of the exhaust air at the higher ventilation rate was 59.6 per cent while, at the lower ventilation rate, it was 65.2 per cent. This indicates that more water vapour was removed per hour by the higher ventilation rate which was the case when the water vapour was expressed only in terms of time. The ratio of the ventilation rates was 1.27:1.00 while the ratio of the water vapour removal rate per hour was 1.19:1.00. For practical purposes,the higher ventilation rate of 3727 cfm was not justifiable since the mean relative humidity for the lower ventilation rate was within tolerable limits. Insufficient data was available to determine the ventilation rate where the minimum RH occurred. According to Dick and Loader, relative humidity approaches a minimum after which it increases while increasing the ventilation rate (17).

The number of rotors in operation resulted in a significant change

in the WVRR. The exhaust levels and the interaction treatment x exhaust level were highly significant. The variable which accounted for a set of runs following the subsequent set of runs was period. It was found to be highly significant indicating that some parameter was responsible for the means of the first set of runs being significantly higher than the second set within each block. Since the blocks within the replicates and the sequence of the runs were not significantly different, this would imply that little carryover effect from one trial run to another existed.

One and no operating rotors were significantly different from two and three operating rotors whereas the effect of one and no rotors in operation did not produce significant differences in the WVRR (table 9). Also the differences in WVRR were not significant between the two and three rotors except for the first replicate of the three rotors in operation. The non-significance in the difference between three and two operating rotors as regards to WVRR indicates that, if only one rotor was operating in each of the two pits, the effect would be similar to that of three rotors operating. This was likely due to the fact that the rate of slurry circulating in the pit was the same in each case in that if two rotors operated in one pit, the rotors were raised such that the flow rate was approximately the same as for the single rotor.

As shown by the interaction rotor x exhaust level (figure 15), the WVRR for the no rotor treatment is greater than the WVRR for the single operating rotor. During this period in which the rotors were not functioning, the mean ambient temperature was higher than when the single rotor was operating (table 32). This would account for the WVRR being higher since the exchange air would be capable of removing

more moisture. The small increase in relative humidity would also support this view. The ratio of the overall mean WVRR between the straw-bedded housing system and the slatted-floor housing system with no rotors operating was 0.82. Harmon et al (27) found that the ratio of WVRR for a slatted-floor swine barn and a concrete floor swine barn was 0.42.

There are several possible reasons which might explain the difference in this ratio. In this experiment, the slatted floor was compared with a straw bed. The straw bed would have more surface area than the concrete floor and a higher surface temperature as a result of the heating through decomposition of the manure pack. Thus the rate of evaporation should be greater and the ratio should be less. However, the ratio was higher possibly due to the fact that the environmental conditions for each housing system were different in that the mean ambient temperature of the slatted-floor housing system consistently was higher than that of the straw-bedded by 5-8^{o}F. Also the animals weighed more in the no rotor treatment since this phase of the study was carried out in the latter part of the experiment. Other parameters accounting for the ratio difference might include the difference in the ratio of solid surface to gap areas between the slats in the swine housing and in the cattle housing since the evaporation of moisture deposited on the slats varies directly as the surface area of the slats.

When no rotors were functioning, the WVRR was higher at the upper exhaust level. This would indicate that if no agitation of the slurry is occurring, the major proportion of the water vapour was produced above the slats by the respiration of the animals such that the WVRR by the upper level exhaust exceeded that of the lower exhaust level.

With the rotors functioning, the site of the major proportion of the water vapour was below the slats due to the increased evaporation caused by the agitation process. This would suggest,therefore, that, if no agitation is occurring within the storage pits, the stale air should be exhausted at or above the floor level in order to maximize the WVRR.

The treatments comprised of three replicates, namely the two ventilation rates in the straw-bedded housing system and the three rotors treatments, were found not to be consistent in that some of the replicates within these treatments were significantly different from each other (table 9). One parameter that could be partly responsible for these differences is the animal liveweight of each housing system in that its rate of increase may not have varied linearly with the rate of increase in WVRR. The regression analysis seemed to support this assumption. For this reason, it was very difficult to compare the rotor treatments since conditions such as liveweight, relative humidity, and temperature changed between treatments.

6.2 Mean Ammonia Concentrations

The overall mean NH_3 removal rates in terms of liveweight and cfm were not significant for the five treatments considered which included the rotor treatments and the two replicates in the straw-bedded housing system. Although insignificant, the treatments indicated that the NH_3 removal rate was higher in the slatted-floor housing than in the straw-bedded area. Research by Taiganides and White indicated that production of NH_3 in litter was greater than that for liquid slurry (54). Less NH_3 removed in the straw-bedded housing system might be due to the fact that the manure pack was removed every three to four weeks, a time

interval which may be too short for a maximum rate of decomposition to have been achieved.

Exhaust levels were highly significant. Higher concentrations of NH_3 were exhausted by the lower exhaust level for every treatment. This would imply that NH_3 is removed most effectively near the site of production. This also discounts the theory of removing the NH_3 at a level where it would accumulate according to its relative density.

The interaction treatment x exhaust level was insignificant but some trends were apparent. In the slatted-floor housing system, some unexpected trends occurred in the rotor treatments in that the NH_3 removal rate for three, two, and one rotor in operation was higher than with no rotors operating (figure 16). The analysis suggested that, as aeration increased, the NH_3 production decreased. The reason why the mean NH_3 removal rate of the no rotor treatment was lower than the other rotor treatments is not apparent. Perhaps, as aeration increased, some of the additional water vapour expelled by the agitation may have combined with the NH_3 as NH_4OH or NH_3- water. Some preliminary work prior to the experiment indicated that, if the sample gas was passed through a condenser before passing it through the infrared analyzer, the readings were approximately half of those without the condenser in some cases. This would indicate that a great deal of the NH_3 exhausted is combined with the water vapour. Further study is required to determine what proportion of the NH_3 exhausted is combined with the water vapour and therefore, undetected by the infrared NH_3 analyzer. From this data, the possibility exists that, with increasing aeration, more water vapour is created and thus more NH_3 reacts with the water vapour such that some proportion is undetectable to the instrumentation

used in this study.

6.3 Mean Carbon Dioxide Concentrations

The overall mean CO_2 removal rates in terms of cfm and liveweight were not significant for the five treatments as considered in the NH_3 analysis. Exhaust level was also insignificant whereas the interaction treatment x exhaust level was significant. The trends of this interaction indicated that the CO_2 removal rate was higher in the straw-bedded housing system than in the slatted-floor housing system (figure 17). This could be due to the CO_2 staying in solution within the liquid slurry and trapped by the scum layer which existed in the two anaerobic pits. In the straw-bedded housing system, the CO_2 removal in the second replicate was greater than the first indicating that the manure pack released more CO_2 or that the animals' rate of production of CO_2 exceeded the rate of their liveweight gain since the ventilation rate was approximately the same for each replicate.

The effect of the first two trial runs followed by the second set of runs was highly significant in which the overall means of the CO_2 removal rate for the first set of runs exceeded the mean value for the second set of trial runs. This implied that equilibrium of the CO_2 being removed as it was produced did not occur. The exhaust level operating during the break period which separated the two sets of trial runs was the one operating during the last trial run of each set. Since the last trial run of Period 1 was the first trial run of Period 2, the exhaust level would operate continuously for five days. This apparently reduced the overall mean CO_2 removal of the first trial run in Period 2. No other reason was apparent. When Period 2 followed Period 1, this effect would not occur since the last trial run in

Period 2 was not the first trial run in Period 1 (table 1).

6.4 Multiple Regression Analysis

A multiple regression analysis was carried out for each housing system and exhaust level for the WVR, NH_3, and CO_2. Some of the regression equations are very complex and lengthy. As a result, tables are provided to show the proportion of squares reduced by each term and thus serve as a means in using these equations on a practical basis. The variation in the dependent variable not accounted for may be due to other parameters not considered. Interactions between the variables were taken into account but perhaps may have been expressed more effectively since non-linear relationships did exist.

6.4.1 Water Vapour Removal Rate Regressions

The multiple regression analyses indicated that, in the slatted-floor housing system, animal weight, temperature and relative humidity accounted for the major proportion in the variation of the WVR. In the straw-bedded housing system, animal weight, ventilation rate and temperature explained the major variation in the WVR. The water consumption of the animals had a negligible effect on the variation in WVR in either housing system. The rotors accounted for more of the variation in WVR at the lower exhaust level than at the upper exhaust level. This would explain the reason why the WVR at the lower exhaust level was higher than that of the upper exhaust level. It also would suggest that the evaporation was not as great from the pits when the stale air was removed by the upper exhaust level. Perhaps because of lack of air movement, the vapour pressure above the slurry was greater than the pressure above the slats, which would reduce the rate of evaporation.

6.4.2 Ammonia Removal Rate Regressions

In the NH_3 regression analysis, only the slatted-floor housing system was considered. At the lower exhaust level, the CO_2 x RH interaction and the number of operating rotors accounted for the major variation in the NH_3 concentrations. This would indicate that, as CO_2 and the relative humidity increased, the NH_3 concentration would decrease while the NH_3 would increase with an increase in the number of rotors in operation. The relative humidity and the rotors accounted for 54 per cent of the variation in the NH_3 exhausted at the upper exhaust level. The accuracy of this prediction equation is questionable because of the low percentage of the sum of squares reduced and the high intercept although it does indicate that the relative humidity and rotors are primarily responsible for the variation in the NH_3 concentrations exhausted.

6.4.3 Carbon Dioxide Rate Regressions

In the CO_2 regression analysis, prediction equations were determined for each exhaust level in the slatted-floor housing system and for the straw-bedded housing system where the exhaust levels were combined as one exhaust level. This data was combined since no significant differences were found as determined by the analysis of variance and because the data obtained for the straw-bedded housing system was only based on 40 days while that of the slatted-floor housing system was based on 80 days.

In the slatted-floor housing system, 81 per cent of the variation in the CO_2 concentration removed at the upper exhaust level was explained by the interaction ventilation rate x number of rotors operating. This could indicate that an increase in the ventilation rate or the number of rotors in operation would decrease the CO_2 concentration of the

exhaust air. A decrease in the number of rotors operating therefore would suggest that anaerobic decomposition will release more CO_2 than aerobic digestion. The CO_2 exhausted at the lower exhaust level also indicated that an increase in rotors decreased the concentration of CO_2 removed. In the straw-bedded housing system, the animal liveweight accounted for 81 per cent of the variation in the CO_2 exhausted.

In both housing systems, the CO_2 concentrations exhausted increased as the experiment progressed. This increase was considered to be due to the increasing animal size and, in the slatted-floor unit, also due to the progressive shut-down of the rotors. The regression analysis would suggest that the CO_2 concentration was more sensitive to the change in the number of operating rotors than the change in the liveweight of the animals in the slatted-floor housing system whereas, in the straw-bedded housing system, the animal liveweight was responsible for the major variation in the CO_2 exhausted.

6.5 Moisture Balance.

The parameters considered in the moisture balance were:

a) moisture entering and leaving the housing system via the exchange air,

b) water consumption of the animals,

c) moisture content of the feed fed to the animals,

d) accumulation of moisture in the pits or straw bed, and

e) moisture released by the animals.

Of the total moisture introduced into the housing systems, the percentage removed by ventilation was found to range from 47 to 73 per cent. With no rotors operating, approximately 50 per cent of the moisture entering the slatted-floor housing system was removed while

62 to 73 per cent was removed with two or three rotors operating. The straw-bedded housing system was comparable to the one rotor treatment with respect to the percentage moisture removed (table 32).

In the moisture balance, several interesting trends were observed. The relative humidity decreased with decreasing numbers of rotors operating since less evaporation occurred. Also the moisture introduced by the incoming air increased as the outside temperatures increased, the experiment running between the months of December and May. Table 32 illustrates the fact that the comparison between the housing systems was quite difficult in that the variables such as temperature, animal liveweight and relative humidity differed in each housing system and for each operating exhaust level. Thus, the liveweight and cfm as a common denominator for WVRR might be questionable in that the common denominator may not have been representative of the WVRR that would have occurred had all the variables been constant.

The error in the moisture balance was also of interest since, as a percentage of the water input, this error ranged between 1.7 and 16.5 per cent. The largest error was considered to be that involving the measurement of the moisture accumulating for each trial run since this accumulation was a very small percentage of the accumulated moisture already present in the pits or straw bed.

6.6 Gas Sampling at Animal Level and In Individual Exhaust Ducts

Several interesting observations were made regarding sampling the CO_2 and NH_3 at the animal level and in the individual side ducts. At the animal level in the slatted-floor housing system, the NH_3 concentration was less than that of the main exhaust duct at the lower

exhaust level. The NH_3 concentration at the animal level, however, exceeded that of the main exhaust duct at the upper exhaust level. This points out that the NH_3 production from the slurry is removed most effectively nearest the site of production.

The CO_2 concentrations at animal level in the slatted-floor housing system always exceeded the concentration of CO_2 in the exhaust air of the main exhaust duct at both exhaust levels. This would indicate that the major proportion of the CO_2 was produced by the animals since the concentration decreases from the source to the exhaust location by diffusion. In the straw-bedded housing system, the CO_2 and NH_3 concentrations at animal also exceeded those measured in the main exhaust outlet for each exhaust level.

With regard to the individual exhaust ducts of each exhaust level, one interesting observation was noted at the upper exhaust level with respect to the CO_2 removal in the slatted-floor housing system. The concentration of the CO_2 exhausted by the west duct was consistently higher than that of the east duct. This was probably due to the fact that the area along the east wall was vacant (figure 1). This again illustrates the fact that the concentration of CO_2 decreases as it approaches the exhaust duct through diffusion. The animals were nearer to the west duct than the east duct such that more CO_2 diffusion occurred on the east side of the building. At low level exhausting, this difference was not noticeable implying there was equal diffusion of the CO_2 on each side of the building.

6.7 Carbon Dioxide Output of a Beef Animal

A carbon balance was determined in order to estimate what proportion of the CO_2 exhausted was actually produced by the animals. This carbon

balance was based on feed intake. It was found that approximately all the CO_2 was produced by the animals, thus leaving a small proportion produced by the waste decomposition and eight barn swallows who unfortunately found themselves confined to the facility for the duration of the experiment.

Also of interest was the fact that approximately one half of the CO_2 present in the environment of the cattle during the coldest weather entered the housing units via the incoming air as a result of the CO_2 released from the induct heaters. This type of heating system used as a supplementary heat source, might have limitations under severe cold conditions in certain situations through the addition of further CO_2 to that respired by the livestock and generated by waste decomposition. Even though CO_2 tolerance limits for livestock may not actually be reached, there is the possibility that, in combination with other atmospheric contaminants including dust, the levels may be imposing some environmental stress on the livestock or poultry confined within the building.

6.8 Instrumentation Limitations

6.8.1 Ventilation Rate Measurements

In measuring the mean ventilation rate for each trial run, several difficulties occurred since the air flow was not monitored on a continuous basis. The wind speed and its direction caused the air flow of the fans to fluctuate at times particularly if the wind blew into the inlet. The wind also appeared to have a suction effect on the exhaust stacks.

The bird screens on the duct inlets at times were coated with frost to the extent that air flow was restricted somewhat. In the daytime, they were checked periodically and cleaned if necessary but,

during the night, frost build-up may have occurred without such action being taken.

6.8.2 Temperature Instrumentation

Determining the wet-bulb temperature of the inlet air was considered to be the main problem. The reason for this was that a large temperature differential existed between the dry and wet-bulb temperature especially in cold weather. It was found that the wick had to cover approximately four inches of the thermocouple lead in order to inhibit the heat from travelling down the thermocouple lead and thus heating the junction. The wet-bulb was checked frequently with a sling psychrometer and, at times, was found to have an error of up to $3^{\circ}F$ for no apparent reason since usually the wet-bulb temperature seemed to be in agreement with the sling psychrometer reading. During cold weather, the temperature differential between wet and dry-bulb readings was in excess of $15^{\circ}F$.

Corrosion of the thermocouples was a further problem in the exhaust ducts. This was considered to be most probably due to the presence of both NH_3 and H_2S in the exhaust air.

6.8.3 Ammonia Infrared Analyzer

The NH_3 infrared analyzer presented a few problems during the experiment. The instrument seemed to be very sensitive to a change in temperature. To minimize this situation somewhat, a thermostatically controlled heater was used to heat the instrument room. Upon completion of the experiment, the infrared sources in the instrument also were found to be weak. As the experiment progressed, the gain factor had to be increased to compensate for the weakening sources. The effect of the water vapour on the NH_3 present was

difficult to ascertain. There was some evidence that the NH_3 analyzer was taking into account NH_3 which had combined with water vapour in addition to NH_3 gas but whether it accounted for all the NH_3 present in various forms is very doubtful.

6.8.4 Cattle Scale

The cattle liveweight was used as a common denominator for the data analyzed. The accuracy of the scale was open to question on occasion during the experiment since less significant changes in weight were apparent. At the subsequent weighing, the weights would show a significant change. As a result, a regression analysis was carried out on the cattle weights with respect to time in order to determine the actual gain per day. In the straw-bedded housing system, the correlation between the animal liveweight and time was 0.98 while in the slatted-floor housing system the correlation was 0.99. The prediction equations were then used to predict the animal weights for each trial run. The equations were as follows:

$$SBAN = 434.7 + 2.4D$$

$$SFAN = 411.5 + 2.7D$$

where SBAN = weight per animal in the straw-bedded housing system (lb),

SFAN = weight per animal in the slatted-floor housing system (lb),

and D = number of days from October 24, 1970.

The equations apply only to the animal weights during the experimental period from 24th of October, 1970 to 1st of May, 1971.

6.8.5 Determination of the Moisture in the Straw Bed and Pits

Calculating the moisture content of the straw bed and the pits presented a few problems. Determining the volume of the straw bed with

a good degree of accuracy was difficult because of the inconsistency in the depth of the straw bed. The samples obtained for moisture determination were as representative of the straw bed as possible but may be recognized as a source of error.

The collection of samples for the determination of the moisture content of the slurry in the anaerobic pits was also a problem in that the wastes settled due to the absence of agitation. Measuring the depth of the slurry in these pits presented a further problem in that a scum layer existed on the surface. The measuring probe tended to include this layer even though an attempt was made to mix the scum with the slurry at the measuring point before measurement. These readings were questioned as they seemed to fluctuate for no apparent reason. Perhaps some type of floating mechanism would have been more reliable. The slurry was measured in the same location every time in each pit in an attempt to minimize errors.

7. SUMMARY AND CONCLUSIONS

A summary of results obtained from this project and the conclusions drawn are as follows:

1. Significant differences between the water vapour removal rates existed for the two exhaust levels in the comparison of the straw-bedded housing system and the slatted-floor system with three rotors in operation.
2. The exhaust level by housing system interaction was significant. It was found that practical differences existed between the water vapour removal rates for both exhaust levels in the slatted-floor housing system while no practical differences in water vapour removal rates were found for the two exhaust levels in straw-bedded housing system. The lower exhaust level removed the higher rate of water vapour in both housing systems.
3. The effect of rotors on the water-vapour removal rate was significant in that the rates with one and no operating rotors were significantly lower than with two and three operating rotors.
4. With no rotors operating in the slatted-floor housing system, the ratio of the water vapour removal rate for the slatted-floor housing system to that of the straw-bedded housing system was 0.82.
5. Vaporized moisture is removed most effectively nearest the site of production. In the slatted-floor housing system, it was found that that the upper level exhausting system removed more water vapour when no rotors were operating while the lower level exhausting system removed more water vapour when the rotors were operating.

6. The moisture balance carried out for both housing systems indicated that 47 to 73 per cent of the total moisture input was removed by ventilation.
7. The difference in the mean water vapour removal rates for the two ventilation rates in the straw-bedded system was significant in that, at the lower ventilation rate, more water vapour was removed than at the higher rate when expressed in terms of cubic feet per minute and liveweight.
8. Significant differences in ammonia concentrations existed between the exhaust levels while the interaction exhaust level by housing treatments were insignificant. It was found that the lower exhaust level removed more ammonia than the upper exhaust level for each housing treatment.
9. Carbon dioxide concentrations did not differ significantly between levels and housing treatments while their interaction was significant. The removal rate of carbon dioxide was greatest in the straw-bedded housing system.
10. The multiple regression analysis indicated that, of the independent variables, animal weight, temperature, and relative humidity accounted for the major portion in the variation of the water vapour removal rate in the slatted-floor housing system while animal weight, ventilation rate and temperature explained the major portion of the variation in the water vapour removal rate in the straw-bedded housing system.
11. Regression analysis indicated that an increase in the number of operating rotors and ventilation rate decreased the CO_2 concentration of the exhaust air in the slatted-floor housing

system while, in the straw-bedded housing system, the animal liveweight accounted for the major proportion of the variation in the CO_2 concentration of the exhausted air.

12. A comparison of the NH_3 concentrations in the vicinity of the animals with the concentrations exhausted by each exhaust level indicated that the gas was more effectively removed closest to the primary site of production, that is, the liquid manure in the slatted-floor housing system.

13. A carbon balance on the beef cattle indicated that, for practical purposes, all the carbon dioxide may be considered as being produced by the cattle through respiration with a negligible quantity arising from decomposition of the wastes.

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APPENDIX 1. DETAILS OF FAN CAPACITY MEASUREMENT.

The procedure used has been described by Jorgenson (35) and was carried out as follows:

For each inlet duct in each housing system, the cross section of the rectangular duct was divided into 25 equal rectangular areas in which the velocity pressure was measured at the center of each. The average velocity pressure was calculated by the root mean square method as follows

$$VP = \left(\frac{\sqrt{VP_1} \cdot \cdot \cdot \cdot \cdot \cdot \sqrt{VP_2}}{25}\right)^2$$

where VP = average velocity pressure (inches).

The actual air flow rate was then calculated from the following formula:

$$CFM = 1096.5\ A \sqrt{\frac{V.P.}{\partial}}$$

where CFM = volume rate (cubic feet per minute),

A = area of duct at point of measurement (square feet), and

∂ = air density (.075 lb per cubic feet) at 70°F and 30 % R.H.

The average air flow rates for each trial run are presented in Appendix 8.

APPENDIX 2. METHOD OF CALCULATING THE MOISTURE CONTENT OF THE MANURE PACK.

The depth of the manure pack at the center of each grid within each pen was measured. The average depth for each pen was then obtained from these depth measurements and multiplied by their respective areas to determine the volume of each manure pack.

The three core samples from each pen were weighed and a portion thereof was oven dried at 250^{o}F to constant weight in order to determine the moisture content. The volume of each core sample was determined by multiplying the average depth where the core samples were taken by its area.

The following formula was used to calculate the water present in the manure pack for each pen.

$$WP = \frac{Vol_{SB}}{Vol_{S}} \times \frac{W_{ST}}{W_{OS}} \times MC_{S}$$

where WP = weight of water in the manure pack (lb),

Vol_{SB} = volume of manure pack (cubic feet),

Vol_{S} = volume of sample, (cubic feet),

MC_{S} = weight of water in oven sample (lb),

W_{TS} = weight of total sample (lb), and

W_{OS} = weight of oven sample (lb).

The total amount of moisture for the entire manure pack was then determined by the addition of the individual pens. This procedure was done before and after each trial run. The difference of these indicated the accumulation of water in the manure pack for the trial run in question.

APPENDIX 3. CARBON BALANCE FOR A STEER IN THE SLATTED-FLOOR HOUSING SYSTEM.

Period: March 18 - April 28

Average weight of animal = 870 lb

Number of animals = 38

Average gain per day = 2.7 lb

Average CO_2 content of exhausted air produced by animals and their waste = 1210 ppm

Average ventilation rate = 3030 cfm = 4.36×10^6 cubic feet per day (CFD)

Feed: Grain = 15.3 lb — 86.5 % dry matter (DM)

Haylage = 6.7 lb — 45 % DM

Dry Matter: $15.3 \times 86.5 = 13.2$

$6.7 \times 45 = \underline{3.0}$

16.2 lb DM

Digestibility = 80%

DM digestible = $.8 \times 16.2 = 13.0$ lb

Feed: protein 15 % — protein - 53 % carbon

carbohydrate 85 % — carbohydrate - 40% carbon

Carbon in Digestible Feed = 5.43 lb

<u>Carbon Retained in Liveweight Gain</u>

Tissue = 30% DM

Gain Per Day = 2.7 lb

Carbon = 51 % (Dry Tissue)

Carbon retained = .41 lb

<u>Carbon expired</u> = 5.02 lb

$CH_4 \simeq .1CO_2$

Carbon expired as CO_2 = 4.52 lb

$$\text{WT. of } CO_2 = \frac{44}{12} \times 4.52 \times 454 \text{ gm/lb} = 7500 \text{ gm}$$

1 gm equivalent CO_2 = 44 gm

1 gm equivalent C = 12 gm

1 gm equivalent = 22.4 litres

$$\text{Volume of } CO_2 = 22.4 \times \frac{7500}{44} = 3820 \text{ litres}$$

CO_2 produced per animal/day = 135 cfd

= 31 ppm

Total production (38 animals) = 1177 ppm

CO_2 removed = 1210 $\pm$ 100 ppm

= 139 $\pm$ 11 cfd/animal

= 31.9 ppm/animal

APPENDIX 4. CARBON BALANCE FOR A STEER IN THE STRAW-BEDDED HOUSING SYSTEM.

Period: Feb. 4 - Feb. 24

Average weight of animal = 710 lb

Number of animals = 37

Average gain per day = 2.7 lb

Average CO_2 content of air produced by animals and their waste = 1115 ppm

Mean ventilation rate = 2968 cfm = 4.28×10^6 cfd

Feed: Grain = 12.7 lb   86.5 % DM

Haylage = 15.3 lb   42.0 % DM

Dry Matter (DM) of feed = 17.4 lb

Digestibility = 80 %

DM digestible = .8 x 17.4 = 13.9 lb

Protein = 15 %   Protein - 53 % carbon

Carbohydrate = 85 %   Carbohydrate - 40 % carbon

Carbon in digestible feed = 5.83 lb

Carbon Retained in Liveweight Gain

Tissue = 30 % DM

Gain Per Day = 2.7 lb

Carbon = 51 % (Dry Tissue)

Carbon retained = .41 lb

Carbon expired

Carbon expired = 5.42

$CH_4 \simeq .1CO_2$ (Volume)

Carbon expired as CO_2 = 4.88 lb

Weight of $CO_2 = \frac{44}{12} \times 4.88 \times 454$ gm/lb

= 8123 gm/day

Volume of $CO_2 = \frac{22.4 \times 8123}{44}$

= 4136 litres/day

CO_2 produced per animal/day

= 146 cfd = 34.1 ppm

Total production (37 animals) = 1262 ppm.

1 gm equivalent CO_2 = 44 gm

1 gm equivalent C = 12 gm

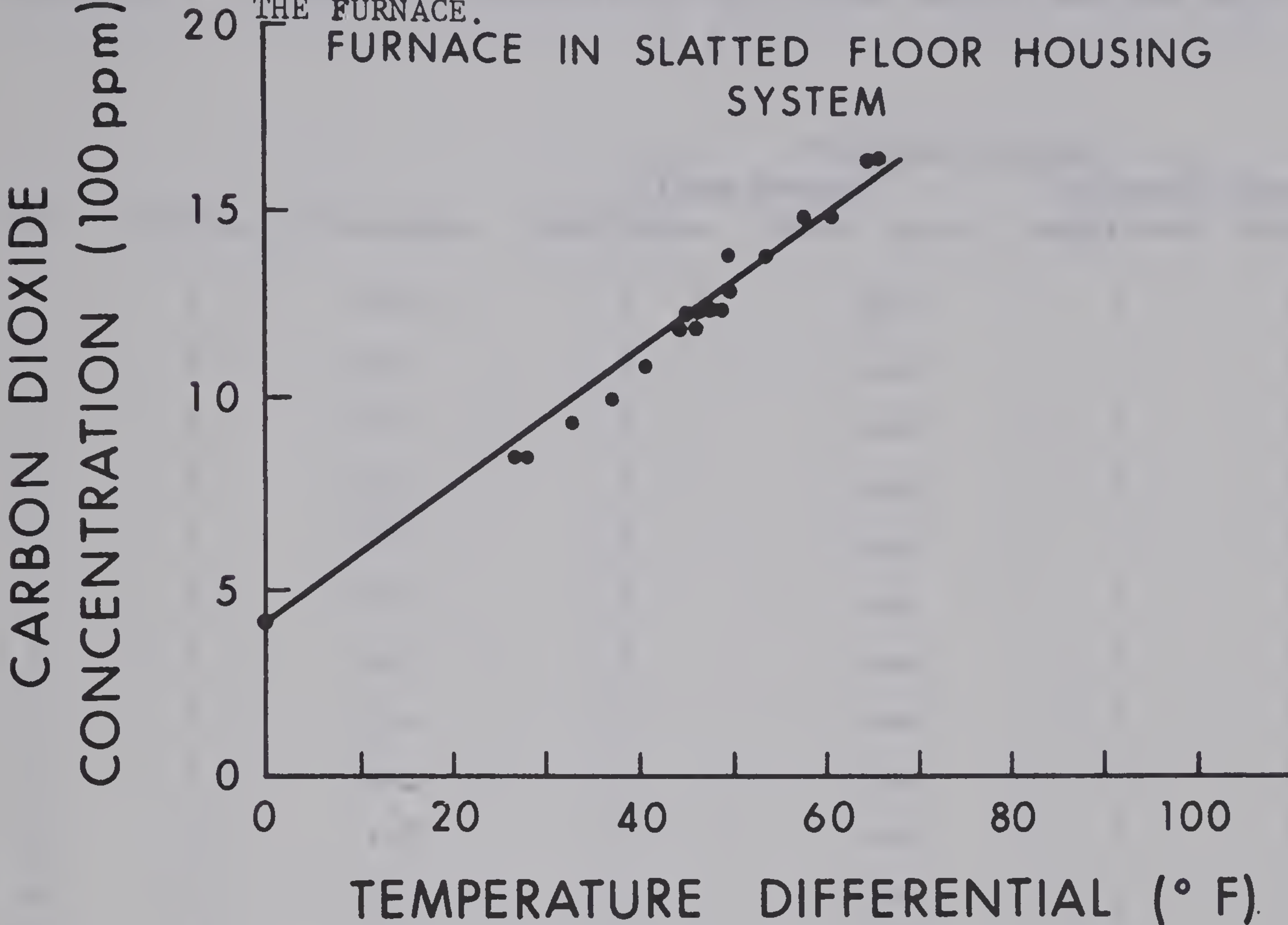
1 gm equivalent = 22.4 litres

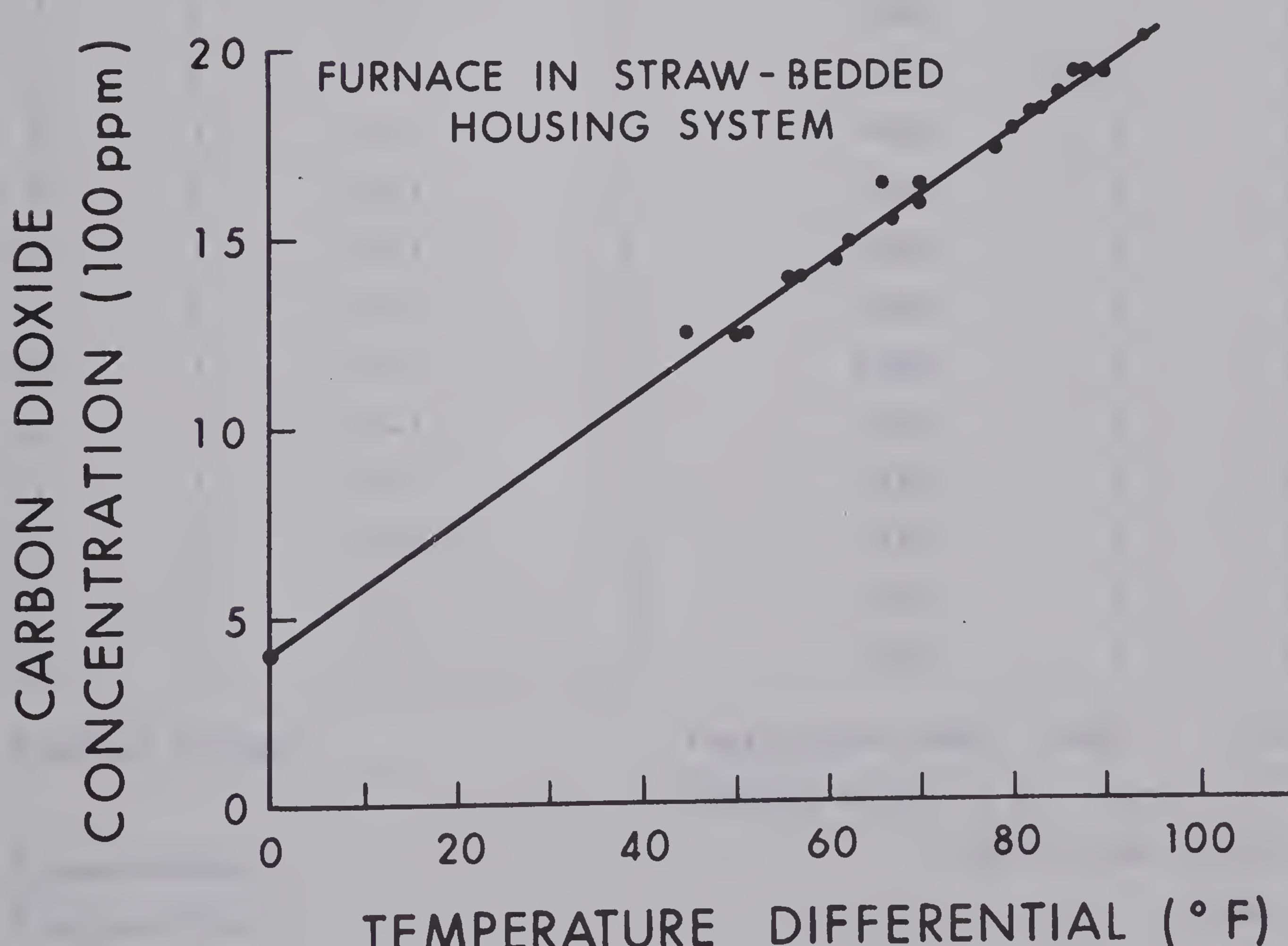
CO_2 removed = 1115 $\pm$ 100 ppm

= 129 $\pm$ 11 cfd/animal

= 30.1 ppm/animal

APPENDIX 5. CALIBRATION CURVES TO DETERMINE THE CARBON DIOXIDE ENTERING THE HOUSING SYSTEM BASED ON TEMPERATURE DIFFERENTIALS UPSTREAM AND DOWNSTREAM FROM THE FURNACE.





APPENDIX 6. TREATMENT COMBINATIONS FOR WATER VAPOUR REMOVAL RATE.

			Housing System			
			Straw-Bedded		Slatted-Floor	
Run	Period	Sequence	Replicate	Vent. Rate	Replicate	Rotors
1	1	2-1*	1	low	1	3
1	2	1-2	1	low	1	3
2	1	1-2	1	low	1	3
2	2	2-1	1	low	1	3
3	1	2-1	2	low	2	3
3	2	1-2	2	low	2	3
4	1	1-2	2	low	2	3
4	2	2-1	2	low	2	3
5	1	2-1	3	low	3	3
5	2	1-2	3	low	3	3
6	1	1-2	3	low	3	3
6	2	2-1	3	low	3	3
7	1	2-1	1	high	1	2
7	2	1-2	1	high	1	2
8	1	1-2	1	high	1	2
8	2	2-1	1	high	1	2
9	1	2-1	2	high	1	1
9	2	1-2	2	high	1	1
10	1	1-2	2	high	1	1
10	2	2-1	2	high	1	1
11	1	2-1	3	high	1	0
11	2	1-2	3	high	1	0
12	1	1-2	3	high	1	0
12	2	2-1	3	high	1	0

Housing System	Ventilation Rate	High		Low	
	Exhaust Level	2	1	2	1
Straw-bedded		3693	3760	2992	2943
Slatted-floor				3032	3060

2-1* 2 - lower exhaust level

1 - upper exhaust level

APPENDIX 7. TREATMENT COMBINATIONS FOR AMMONIA AND CARBON DIOXIDE.

Run	Period	Sequence	Housing System
1	1	2-1*	A1**
1	2	1-2	A1
2	1	1-2	A1
2	2	2-1	A1
3	1	2-1	B3++++
3	2	1-2	B3
4	1	1-2	B3
4	2	2-1	B3
5	1	2-1	A2***
5	2	1-2	A2
6	1	1-2	A2
6	2	2-1	A2
7	1	2-1	B2+++
7	2	1-2	B2
8	1	1-2	B2
8	2	2-1	B2
9	1	2-1	B1++
9	2	1-2	B1
10	1	1-2	B1
10	2	2-1	B1
11	1	2-1	B0+
11	2	1-2	B0
12	1	1-2	B0
12	2	2-1	B0

2-1* 2 - lower exhaust level
1 - upper exhaust level

A1** straw-bedded housing system (1st replicate)

A2*** straw-bedded housing system (2nd replicate)

B3++++ slatted-floor housing system (3 rotors)

B2+++ slatted-floor housing system (2 rotors)

B1++ slatted-floor housing system (1 rotor)

B0+ slatted-floor housing system (no rotors)

APPENDIX 8. WATER VAPOUR REMOVAL RATES AND THE MOISTURE BALANCE DATA.

The water vapour removal rates and the moisture balance calculations for all the different treatments are presented on the following pages. The following variables appear in the columns and their abbreviations are defined as follows:

ANWT = animal weight (lb),

CAL = calculated moisture accumumation based on moisture balance (lb per trial run),

CON = water consumed (lb per trial run),

E.L = exhaust level 2 - lower exhaust level
1 - upper exhaust level,

GR = moisture content of grain fed (lb),

HAYL = moisture content of haylage fed (lb),

INL = water vapour entering the building via the inlet duct, (lb per trial run),

MEAS = measured moisture accumulation (lb per trial run),

OUT = water vapour exhausted through the outlet duct (lb per trail run),

P = period,

R = run number,

RH = relative humidity (per cent),

TANWT = total animal weight (10,000 lb liveweight),

TEMP = ambient air temperature (°F),

VENT = ventilation rate (cubic feet per minute), and

VOL = volume of manure pack (cubic feet per trial run)

WVRR = water vapour removal rate (lb per 10,000 lb liveweight per 1000 cubic feet per minute).

Reference may be made to Appendix 6 for an explanation of the run number, period and exhaust level sequence. The temperature data used to derive the WVRR values were not included since no analysis was attempted as to temperature trends.

MOISTURE DATA FOR THE SLATTED-FLOOR HOUSING SYSTEM

R	P	E.L	INL	OUT	CON	ACCUMULATION MEAS	ACCUMULATION CAL	ANWT	GR	HAYL
1	1	2	1723.	5675.	4322.	1718.	863.	530.	92.	401.
1	1	1	1717.	5003.	3372.	2129.	586.	535.	94.	407.
1	2	1	1387.	4857.	3452.	1292.	488.	543.	101.	415.
1	2	2	1234.	5122.	3611.	1601.	237.	549.	99.	415.
2	1	1	4577.	6419.	3512.	1928.	2239.	601.	111.	458.
2	1	2	2124.	5312.	3606.	1317.	987.	606.	111.	458.
2	2	2	2217.	4591.	3299.	1504.	1512.	615.	114.	473.
2	2	1	2034.	4006.	3748.	1521.	2365.	620.	116.	473.
3	1	2	2287.	5091.	3495.	1727.	1119.	628.	84.	344.
3	1	1	2512.	4976.	3598.	2354.	1629.	634.	100.	395.
3	2	1	2803.	5509.	3157.	1731.	1003.	642.	108.	444.
3	2	2	2695.	5754.	3229.	429.	740.	648.	114.	456.
4	1	1	2352.	4761.	3932.	2952.	2095.	656.	116.	456.
4	1	2	1902.	4942.	3460.	868.	1040.	661.	116.	504.
4	2	2	2167.	4809.	3838.	2135.	1765.	670.	117.	452.
4	2	1	2221.	4536.	3522.	1735.	1838.	675.	122.	509.
5	1	2	2153.	5018.	3435.	1634.	1196.	683.	118.	508.
5	1	1	2283.	5049.	3722.	2120.	1602.	689.	126.	521.
5	2	1	2649.	5262.	3802.	2053.	1869.	697.	130.	550.
5	2	2	2907.	5829.	4061.	2219.	1840.	703.	137.	564.
6	1	1	2154.	5213.	3691.	1732.	1353.	711.	134.	587.
6	1	2	2152.	5490.	2971.	2131.	352.	716.	146.	573.
6	2	2	2284.	4960.	3556.	1931.	1431.	724.	147.	404.
6	2	1	2586.	4977.	3707.	2098.	1822.	730.	157.	349.

MOISTURE DATA FOR THE SLATTED-FLOOR HOUSING SYSTEM

						ACCUMULATION				
R	P	E.L	INL	OUT	CON	MEAS	CAL	ANWT	GR	HAYL
7	1	2	2029.	5436.	4529.	1813.	1557.	738.	154.	281.
7	1	1	2020.	4551.	4147.	1300.	2027.	744.	146.	265.
7	2	1	2309.	4938.	3545.	1100.	1281.	752.	150.	215.
7	2	2	2853.	5715.	3643.	1300.	1235.	757.	156.	298.
8	1	1	2610.	5426.	3445.	2282.	1085.	766.	160.	296.
8	1	2	2539.	5865.	3848.	1500.	939.	771.	147.	270.
8	2	2	2356.	5656.	4225.	1509.	1309.	779.	149.	235.
8	2	1	2571.	5278.	3906.	2532.	1523.	785.	149.	176.
9	1	2	1883.	4439.	3498.	2164.	1243.	793.	141.	160.
9	1	1	2050.	4353.	3452.	1962.	1546.	799.	152.	245.
9	2	1	2445.	4770.	2775.	2359.	923.	807.	166.	307.
9	2	2	2288.	4961.	3579.	1965.	1259.	812.	160.	192.
10	1	1	2920.	5082.	5278.	2458.	3503.	834.	153.	234.
10	1	2	3268.	5641.	3912.	3141.	1920.	840.	157.	225.
10	2	2	3061.	5634.	3986.	2237.	1842.	848.	163.	266.
10	2	1	3669.	5054.	4131.	1997.	3212.	854.	167.	299.
11	1	2	3281.	5617.	4895.	2534.	3009.	862.	170.	280.
11	1	1	2544.	5062.	5851.	4786.	3763.	867.	160.	270.
11	2	1	3920.	6229.	4240.	1532.	2348.	875.	144.	274.
11	2	2	4650.	7081.	4851.	1499.	2887.	881.	180.	287.
12	1	1	4174.	7123.	4809.	3561.	2310.	889.	181.	268.
12	1	2	3020.	5686.	4339.	2095.	2103.	895.	176.	254.
12	2	2	3243.	5759.	4164.	2925.	2110.	903.	180.	281.
12	2	1	3634.	6413.	4910.	2324.	2622.	908.	180.	311.

MOISTURE DATA FOR THE STRAW-BEDDED HOUSING SYSTEM

R	P	E.L	INL	OUT	CON	ACCUMULATION MEAS	ACCUMULATION CAL	ANWT	GR	HAYL
1	1	2	2383.	4905.	3366.	1791.	1341.	539.	93.	404.
1	1	1	2368.	4706.	3480.	1791.	1644.	544.	94.	407.
1	2	1	2100.	5254.	3468.	846.	783.	551.	93.	376.
1	2	2	2034.	5311.	3764.	2302.	970.	556.	96.	387.
2	1	1	3650.	6399.	4044.	2164.	1799.	602.	98.	405.
2	1	2	2147.	4659.	3662.	1563.	1650.	607.	97.	403.
2	2	2	2012.	4662.	3783.	3434.	1651.	614.	99.	419.
2	2	1	1720.	4231.	3515.	3400.	1528.	619.	103.	421.
3	1	2	2185.	4216.	3700.	3739.	2158.	626.	96.	393.
3	1	1	3109.	5096.	4059.	1887.	2544.	631.	96.	376.
3	2	1	2689.	4224.	4019.	1625.	2991.	639.	99.	408.
3	2	2	1922.	4057.	3585.	3120.	1975.	643.	105.	421.
4	1	1	1986.	4181.	4012.	1413.	2359.	651.	110.	432.
4	1	2	2060.	4654.	3797.	230.	1806.	656.	114.	490.
4	2	2	2091.	4539.	4093.	3440.	2212.	663.	117.	450.
4	2	1	1984.	4721.	3847.	1691.	1712.	668.	116.	486.
5	1	2	2161.	4807.	3835.	1479.	1824.	675.	120.	516.
5	1	1	2311.	5004.	3647.	1003.	1562.	680.	118.	490.
5	2	1	2691.	5054.	3667.	2276.	1946.	687.	123.	519.
5	2	2	2657.	5438.	3620.	1744.	1437.	692.	124.	524.
6	1	1	2254.	5048.	4215.	3111.	2096.	699.	126.	549.
6	1	2	2299.	5240.	3774.	492.	1499.	704.	129.	537.
6	2	2	2303.	4981.	3770.	3949.	1659.	711.	140.	427.
6	2	1	2245.	4666.	3868.	1311.	1924.	716.	144.	333.

MOISTURE DATA FOR THE STRAW-BEDDED HOUSING SYSTEM

R	P	E.L	INL	OUT	CON	ACCUMULATION VOL	CAL	ANWT	GR	HAYL
7	1	2	1933.	5520.	3733.	750.	550.	723.	139.	260.
7	1	1	1686.	5463.	4033.	836.	676.	728.	150.	269.
7	2	1	2344.	5599.	4021.	258.	1121.	736.	146.	209.
7	2	2	2871.	5689.	3957.	377.	1602.	741.	158.	305.
8	1	1	2691.	5763.	3656.	413.	1040.	748.	159.	297.
8	1	2	2475.	6081.	3702.	413.	523.	752.	147.	280.
8	2	2	2609.	5645.	3796.	413.	1108.	760.	134.	214.
8	2	1	2983.	5730.	3644.	558.	1207.	765.	140.	165.
9	1	2	2168.	5329.	3946.	578.	1058.	772.	128.	145.
9	1	1	2270.	5437.	3749.	614.	969.	777.	148.	239.
9	2	1	2988.	5290.	3808.	715.	1950.	784.	156.	288.
9	2	2	2836.	5114.	3453.	759.	1509.	789.	152.	183.
10	1	1	3163.	5145.	3601.	497.	1951.	809.	131.	201.
10	1	2	3469.	5776.	3445.	530.	1501.	813.	149.	214.
10	2	2	3247.	5794.	3502.	582.	1365.	821.	163.	247.
10	2	1	2899.	5588.	3681.	617.	1429.	826.	157.	280.
11	1	2	3764.	6243.	3722.	695.	1673.	833.	160.	270.
11	1	1	3187.	5555.	3927.	721.	1979.	837.	160.	260.
11	2	1	4494.	7079.	3947.	790.	1772.	845.	159.	250.
11	2	2	5284.	7770.	4234.	833.	2171.	850.	163.	260.
12	1	1	4923.	8122.	4257.	870.	1465.	857.	164.	243.
12	1	2	3464.	6622.	4029.	929.	1272.	862.	164.	238.
12	2	2	3478.	6640.	4166.	960.	1426.	869.	165.	257.
12	2	1	4309.	7279.	3957.	1022.	1437.	874.	165.	285.

MOISTURE DATA FOR THE SLATTED-FLOOR HOUSING SYSTEM

R	P	E.L	TEMP	VENT	TANWT	WVRR	RH
1	1	2	63.	3032.	2.014	13.48	70.
1	1	1	62.	3060.	2.033	11.01	64.
1	2	1	59.	3060.	2.063	11.48	68.
1	2	2	55.	3032.	2.086	12.80	83.
2	1	1	63.	3060.	2.284	5.49	77.
2	1	2	59.	3032.	2.303	9.51	73.
2	2	2	55.	3032.	2.337	6.98	73.
2	2	1	52.	3060.	2.356	5.70	70.
3	1	2	62.	3032.	2.386	8.07	65.
3	1	1	61.	3060.	2.409	6.96	65.
3	2	1	56.	4015.	2.440	5.76	64.
3	2	2	52.	4230.	2.462	6.12	74.
4	1	1	60.	3060.	2.493	6.58	63.
4	1	2	61.	3032.	2.512	8.32	65.
4	2	2	59.	3032.	2.546	7.13	67.
4	2	1	58.	3060.	2.565	6.14	65.
5	1	2	61.	3032.	2.595	7.59	65.
5	1	1	61.	3060.	2.618	7.19	66.
5	2	1	61.	3060.	2.649	6.72	68.
5	2	2	63.	3032.	2.671	7.52	71.
6	1	1	61.	3060.	2.702	7.71	68.
6	1	2	61.	3032.	2.721	8.43	71.
6	2	2	61.	3032.	2.751	6.68	65.
6	2	1	60.	3060.	2.774	5.87	65.

MOISTURE DATA FOR THE SLATTED-FLOOR HOUSING SYSTEM

R	P	E.L	TEMP	VENT	TANWT	WVRR	RH
7	1	2	63.	3032.	2.804	8.35	67.
7	1	1	60.	3060.	2.827	6.09	61.
7	2	1	61.	3060.	2.858	6.26	64.
7	2	2	63.	3032.	2.877	6.84	69.
8	1	1	63.	3060.	2.911	6.59	64.
8	1	2	63.	3032.	2.930	7.80	70.
8	2	2	62.	3032.	2.960	7.66	71.
8	2	1	62.	3060.	2.983	6.18	65.
9	1	2	57.	3032.	3.013	5.83	64.
9	1	1	60.	3060.	3.036	5.16	58.
9	2	1	60.	3060.	3.067	5.16	63.
9	2	2	61.	3032.	3.086	5.95	65.
10	1	1	63.	3060.	3.169	4.64	61.
10	1	2	64.	3032.	3.192	5.11	66.
10	2	2	63.	3032.	3.222	5.49	68.
10	2	1	62.	3060.	3.245	2.91	63.
11	1	2	66.	3032.	3.276	4.90	60.
11	1	1	63.	3060.	3.295	5.20	61.
11	2	1	67.	3060.	3.325	4.73	64.
11	2	2	69.	3032.	3.348	4.99	69.
12	1	1	71.	3060.	3.378	5.94	66.
12	1	2	67.	3032.	3.401	5.39	59.
12	2	2	67.	3032.	3.431	5.04	61.
12	2	1	72.	3060.	3.450	5.48	58.

MOISTURE DATA FOR THE STRAW-BEDDED HOUSING SYSTEM

R	P	E.L	TEMP	VENT	TANWT	WVRR	RH
1	1	2	61.	2992.	1.994	8.81	65.
1	1	1	61.	2943.	2.013	8.22	63.
1	2	1	60.	2943.	2.039	10.95	74.
1	2	2	61.	2992.	2.057	11.09	71.
2	1	1	66.	2943.	2.227	8.73	73.
2	1	2	58.	2992.	2.246	7.79	68.
2	2	2	62.	2992.	2.272	8.12	62.
2	2	1	56.	2943.	2.290	7.76	68.
3	1	2	62.	2992.	2.316	6.11	55.
3	1	1	64.	2943.	2.335	6.02	63.
3	2	1	60.	2943.	2.364	4.60	59.
3	2	2	58.	2992.	2.379	6.25	60.
4	1	1	59.	2943.	2.409	6.45	60.
4	1	2	61.	2992.	2.427	7.44	62.
4	2	2	62.	2992.	2.453	6.95	59.
4	2	1	58.	2943.	2.472	7.84	69.
5	1	2	62.	2992.	2.497	7.38	63.
5	1	1	60.	2943.	2.516	7.58	69.
5	2	1	61.	2943.	2.542	6.58	67.
5	2	2	61.	2992.	2.560	7.70	71.
6	1	1	60.	2943.	2.586	7.65	69.
6	1	2	62.	2992.	2.605	7.86	66.
6	2	2	61.	2992.	2.631	7.09	66.
6	2	1	60.	2943.	2.649	6.47	63.

MOISTURE DATA FOR THE STRAW-BEDDED HOUSING SYSTEM

R	P	E.L	TEMP	VENT	TANWT	WVRR	RH
7	1	2	62.	3693.	2.675	7.55	57.
7	1	1	63.	3760.	2.694	7.77	54.
7	2	1	63.	3760.	2.723	6.62	55.
7	2	2	63.	3693.	2.742	5.80	58.
8	1	1	63.	3760.	2.768	6.15	56.
8	1	2	64.	3693.	2.782	7.31	60.
8	2	2	62.	3693.	2.812	6.09	58.
8	2	1	63.	3760.	2.830	5.37	57.
9	1	2	64.	3693.	2.856	6.24	52.
9	1	1	66.	3760.	2.875	6.10	49.
9	2	1	58.	3760.	2.901	4.40	61.
9	2	2	59.	3693.	2.919	4.40	59.
10	1	1	59.	3760.	2.993	3.67	57.
10	1	2	60.	3693.	3.008	4.33	63.
10	2	2	60.	3693.	3.038	4.73	64.
10	2	1	61.	3760.	2.974	5.01	58.
11	1	2	63.	3693.	2.999	4.66	63.
11	1	1	61.	3760.	3.013	4.36	57.
11	2	1	64.	3760.	3.042	4.71	67.
11	2	2	65.	3693.	3.060	4.58	72.
12	1	1	68.	3760.	3.085	5.75	67.
12	1	2	64.	3693.	3.103	5.74	64.
12	2	2	64.	3693.	3.128	5.70	64.
12	2	1	69.	3760.	3.146	5.23	59.

APPENDIX 9. AMMONIA AND CARBON DIOXIDE REMOVAL RATES.

The ammonia and carbon dioxide data collected for all the different treatments and their combinations are presented on the following pages. The concentration values of the ammonia (NH_3) and carbon dioxide (CO_2) are expressed as ppm per 10,000 lb liveweight per 10,000 cubic feet per minute and ppm per 10,000 lb liveweight per 1,000 cubic feet per minute, respectively.

In the heading to each column, the run number (R), period (P), and exhaust level (E.L) are given. These correspond to the run numbers in Appendix 7. It must be noted that gas sampling was carried out in one housing system at a time.

REMOVAL RATES FOR CO2 AND NH3

			HOUSING SYSTEM			
			STRAW		SLATTED	
R	P	E.L	NH3	CO2	NH3	CO2
1	1	2	15.	1397.		
1	1	1	16.	1248.		
1	2	1	9.	1194.		
1	2	2	15.	854.		
2	1	1	5.	1423.		
2	1	2	19.	1373.		
2	2	2	8.	1427.		
2	2	1	10.	1474.		
3	1	2			15.	1338.
3	1	1			10.	1324.
3	2	1			9.	771.
3	2	2			13.	642.
4	1	1			12.	1247.
4	1	2			19.	1036.
4	2	2			21.	1133.
4	2	1			15.	1233.
5	1	2	12.	1376.		
5	1	1	10.	1518.		
5	2	1	10.	1435.		
5	2	2	10.	1554.		
6	1	1	10.	1537.		
6	1	2	14.	1409.		
6	2	2	13.	1355.		
6	2	1	13.	1529.		

REMOVAL RATES FOR CO2 AND NH3

			HOUSING SYSTEM			
			STRAW		SLATTED	
R	P	E.L	NH3	CO2	NH3	CO2
7	1	2			23.	1427.
7	1	1			17.	1179.
7	2	1			17.	1170.
7	2	2			23.	1413.
8	1	1			11.	1264.
8	1	2			21.	1421.
8	2	2			19.	1289.
8	2	1			12.	1131.
9	1	2			15.	1135.
9	1	1			11.	1171.
9	2	1			13.	1130.
9	2	2			21.	1258.
10	1	1			15.	1216.
10	1	2			23.	1190.
10	2	2			25.	1298.
10	2	1			19.	1216.
11	1	2			15.	1239.
11	1	1			12.	1274.
11	2	1			13.	1278.
11	2	2			13.	1268.
12	1	1			13.	1225.
12	1	2			15.	1274.
12	2	2			12.	957.
12	2	1			10.	1043.